Title: A reliable and energy efficient cognitive radio multi-channel MAC protocol for ad-hoc networks

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A Reliable and Energy Efficient Cognitive Radio Multi-Channel MAC Protocol for Ad-Hoc Networks

by

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Abstract

Recent research has shown that several spectrum bands are mostly underutilised. To resolve the issue of underutilisation of spectrum bands across the networks, the concept of Cognitive Radio (CR) technology was envisaged. The CR technology allows Secondary Users (SUs) to acquire opportunistic access to large parts of the underutilised spectrum bands on wireless networks. In CR networks, SUs may scan and identify the vacant channels in the wireless spectrum bands and then dynamically tune their receivers to identify vacant channels and transmitters, and commence communication among themselves without causing interference to Primary/Licensed Users (PUs). Despite the developments in the field of CR technology, recent research shows that still there are many challenges unaddressed in the field. Thus, there is a need to reduce additional handshaking over control and data channels, to minimise large sized control frames and to introduce reliable channel selection process and maintenance of SUs' communication when PUs return to a licensed channel. A fundamental challenge affecting this technology is the identification of reliable Data Channels (DCHs) for SUs communication among available channels and the continuation of communication when the PU returns.

This doctoral research investigates in detail how to resolve issues related to the protocol design for Cognitive Radio Networks (CRNs) on Medium Access Layers (MAC) for Ad-Hoc networks. As a result, a novel Reliable and Energy efficient Cognitive Radio multi-channel MAC protocol (RECR-MAC) for Ad-Hoc networks is proposed to overcome the shortcomings mentioned. After discussing the background, operation and architecture of CR technology, this research proposes numerous platforms and testbeds for the deployment of personal and commercial applications of the CRNs. Side by side, optimised control frames and a reduced number of handshakes over the CCH are suggested to extend the transmitting time for data communication. In addition, the reliable channel selection process is introduced instead of random selection of DCHs for successful data communication among the SUs.

In RECR-MAC, the objective of every SU is to select reliable DCHs, thereby ensuring high connectivity and exchanging the successful data frames across the cognitive network. Moreover, the selection criteria of the DCHs are based on multiple factors, such as an initial selection based on the maximum free time recorded by the SUs over the DCH channel ranking, which is proportional to the number of positive/negative acknowledgements, and the past history of DCHs. If more than two DCHs have an equal value during the second, third and following iterations, then the DCHs are selected based upon the maximum free time. The priorities of the DCHs are then assigned based on Reliable Data Channels, that is, RDCH 1, RDCH 2, RDCH 3, and RDCH 4 respectively (where RDCH 1 and RDCH 2 have the highest priority, DRCH 3 and RDCH 4 have the next priority, and so on). The impacts of channel selection process and Backup Data Channel (BDC) over the proposed RECR-MAC protocol are analysed in combination with comparative benchmark CR-MAC protocols based on the timing diagrams proposed. Finally, the RECR-MAC protocol is validated by using a MATLAB simulator with PU impact over the DCHs, both with and without BDC, and by comparing results, such as communication time, transmitting energy and throughput, with benchmark CR-MAC protocols.

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Declaration

I declare that this thesis is my own work and that the work of others is acknowledged and indicated by explicit references.

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Publications

Faisal F. Qureshi, “EECR-MAC: Energy Efficient Cognitive Radio MAC Protocol for Adhoc Networks,” Wireless Telecommunications Symposium (WTS), 2012, vol., no., pp.1,5, 18-20 April 2012.

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Muhammad T. Zia, Syed S. Shah, Faisal F. Qureshi, “Energy Efficient Cognitive Radio MAC Protocols for Adhoc Network: A Survey,” Computer Modelling and Simulation (UKSim), 2013 UKSim 15th International Conference, On page(s): 140 - 143, 2013

Poster Presentations

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Faisal F. Qureshi, Vladimir Dyo, Xiaohua Feng, “Reliable and Energy Efficient Cognitive Radio MAC Protocol,” IRAC Colloquium on Innovation and Computing, March 2013.

Faisal F. Qureshi, Vladimir Dyo, Xiaohua Feng, “Reliable and Efficient Cognitive Radio MAC Protocol,” Joint International Workshop between ARSR/Swicom, May 2013.

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Vitae

Faisal Fayyaz Qureshi received his BSc in Electronics and Communication Engineering from the University of Engineering and Technology (UET), Lahore, Pakistan on 15th May 2000. He started his professional career with the UET, from 16th May 2000 and worked until 30 September 2001, as a research assistant. From 1st July 2000 to 30th September 2000, he also served in Saudi Arabia as a Telecom Engineer. In March 2001, he qualified with the Cisco Certified Internetwork Experts (CCIE) examination.

From 1st October 2001, he worked as a Network Analyst in San Jose, California, USA. He has also served in Maryland, Virginia, and Florida and held the position of Network Engineer, Team Leader and Manager for Multinational Telecom organisations in the field of Networking and Voice over IP for eight years.

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In March 2011, he started his PhD at the University of Bedfordshire, UK in the area of Reliable and Energy Efficient Cognitive Radio Multi-Channel MAC Protocol for Adhoc Networks under the supervision of Dr. Vladimir Dyo and Dr. Xiaohua Feng.

Abbreviations

AACL	Acknowledgement of Available Channel List
ACK	Acknowledgement
ACL	Available Channel List
ATV	Analog TeleVision
BDC	Backup Data Channel
BO	Back Off
BT	British Telecom
CC-BC	Common Channel Beacon
CCCH	Common Control Channel
CCH	Control Channel
CEPT	European Conference of Postal and Telecommunications Administrations
CR	Cognitive Radio
CRAHN	Cognitive Radio Ad-Hoc Network
CREAM	Cognitive Radio Enabled multi-channel MAC for CRN
CRN	Cognitive Radio Network
CSR	Channel State Receiver
CST	Channel State Transmitter
CSTT	Channel STatus Table
CTS	Clear to Send
CSMA/CA	Carrier Sense Multiple Access Collision Avoidance
CU	Cognitive User

CW	Contention Window
DCH	Data Channel
DCCH	Dedicated Control Channel
DCF	Distribution Coordination Function
DHCP	Dynamic Host Configuration Protocol
DIFS	Distributed Inter Frame Space
DoS	Denial of Services
DSA	Dynamic Spectrum Access
DSAP	Dynamic Spectrum Access protocol
DSSS	Direct Sequence Spread Spectrum
FCC	Federal Communication Committee
DTV	Digital TeleVision
FCL	Free Channel List
FDM	Frequency Division Multiplexing
GSM	Global System for Mobile Communication
IEEE	Institute of Electrical and Electronics Engineering
IFS	Inter Frame Space
ISM	Industrial Scientific and Medical
LTE	Long Term Evolution
MAC	Medium Access Control
NAV	Network Allocation Vector
NDCCH	Non Dedicated Control Channel
OfCom	Office of Communication
OFDMA	Orthogonal Frequency-Division Multiple Access
OU	Opportunistic User
PDC	Primary Data Channel
PDA	Personal Digital Assistants
P_{FA}	Probability of False Alarm

PHY	Physical
P_{succ}	Probability of successful transmits over control and data packets
$P_{un-succ}$	Probability of un-successful transmits over control and data packets
PU	Primary User
QoS	Quality of Service
RBCS	Receiver Based Channel Selection
RC	Rendezvous Channel
R_{DCH}	Reliable Data Channel
RF	Radio Frequency
RTS	Ready to Send
SDR	Software Defined Radio
SIFS	Short Inter Frame Space
SINR	Signal to Interference Noise Ratio
SMS	Short Message Service
SST	Spectrum Status Table
SU	Secondary User
SWITCH	Spectrum access WITh backup CHannel
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TV	TeleVision
UHF	Ultra High Frequency
USRP	Universal Software Radio Peripheral
UWB	Ultra Wide Band
VCS	Virtual Carrier Sensing
VoIP	Voice over Internet Protocol
WARP	Wireless open Access Research Platform
WiMax	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

WPAN	Wireless Personal Area Networks
WRAN	Wireless Regional Area Networks
WSDB	White Space Database
XML	EXtensible Markup Language

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Chapter 1

Introduction

The radio spectrum is overcrowded, but the greater part of it is underutilised [2] [3]. This chapter discusses the background to the wireless technologies that cause this paradox, and explains how wireless communication could be developed to provide a solution. Cognitive Radio (CR) technology is capable of overcoming the existing challenges in wireless technology and provides an effective solution to the inefficient utilisation of networks. The operation of Cognitive Radio Networks (CRNs) will be discussed, including the four key operations between the primary and secondary users: spectrum sensing, spectrum management, spectrum mobility and spectrum sharing. Furthermore, the applications, standards and platforms of CR technology will be discussed in detail. The aim and objectives of this study are highlighted. The last section will discuss the contributions of this thesis.

1.1 Cognitive Radio Networks

The most important and significant characteristic of the Cognitive Radio Ad-Hoc Network (CRAHN) is the successful transmission of information between Secondary Users (SUs), because SUs do not own the channel(s), and the CRAHN which utilises the channel(s) while the Primary Users (PUs) are not active. This section discusses the background of CRNs, the architecture of the technology and current challenges and issues faced by regulatory authorities and service providers. In addition, CRN standards and platforms and their applications will be discussed in the subsections below.

1.1.1 Background

The rapid growth of new and improved wireless applications have drastically increased the demand from the spectrum for better connectivity and services for devices such as laptops, Personal Digital Assistant (PDAs), smart mobile phones, garage door openers, TeleVision (TV) remote controllers, tablets and Bluetooth devices. The allocation of fixed frequency bands to existing and emerging wireless applications based on allocated frequency policies, as shown in Figure 1.1, is a practical approach to eradicate interference between dissimilar wireless devices. However, reports in [4] [3] specify that the static frequency allocation provides the inefficient utilisation of the licensed radio spectrum bands. Therefore, it is obvious that the allocation policies for the existing fixed frequency spectrum should be modified, in order to achieve the effective utilisation of the licensed spectrum bands.

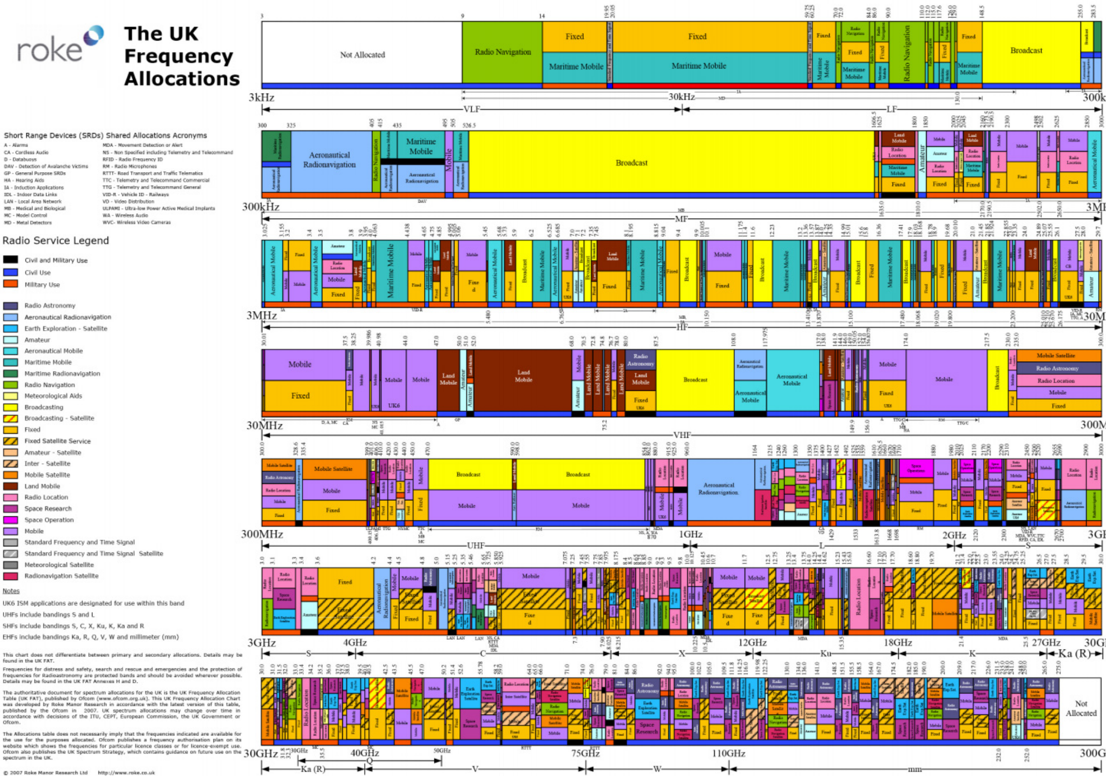

FIGURE 1.1: UK frequency allocation chart [1]

Consequently, the Federal Communication Commission (FCC) and other organisations in [5] [3] have indicated that more than 70% of the licensed spectrum is underutilised, which can result in scarcity of spectrum at any time, particularly in crowded areas. However, in some rural areas, as shown in Figure 1.2, less than 6% of the spectrum bands are occupied. Therefore, CR as an emerging technology has proposed the idea of assigning the spectrum dynamically to wireless technologies [4]. CR technology is a new paradigm in wireless technology, which aims to improve the utilisation of the Radio Frequency (RF) bands. CR technology improves spectrum efficiency by allowing Secondary Users (SUs) to have opportunistic access to large parts of the underutilised spectrum bands in wireless networks [6]. It has also been asserted that CR technology has opened new horizons in emerging areas such as satellite communications, defence, public safety, health monitoring and next generation technologies [7] [8] [9]. In CR networks, the SUs can scan and identify vacant channels in the wireless spectrum bands. Based on the scanned results, the SUs dynamically tune their receivers to the identified vacant channel(s) and the transmitters start the communication amongst themselves without harmful interference with the Primary Users (PUs), also known as Licensed Users and Incumbent Users.

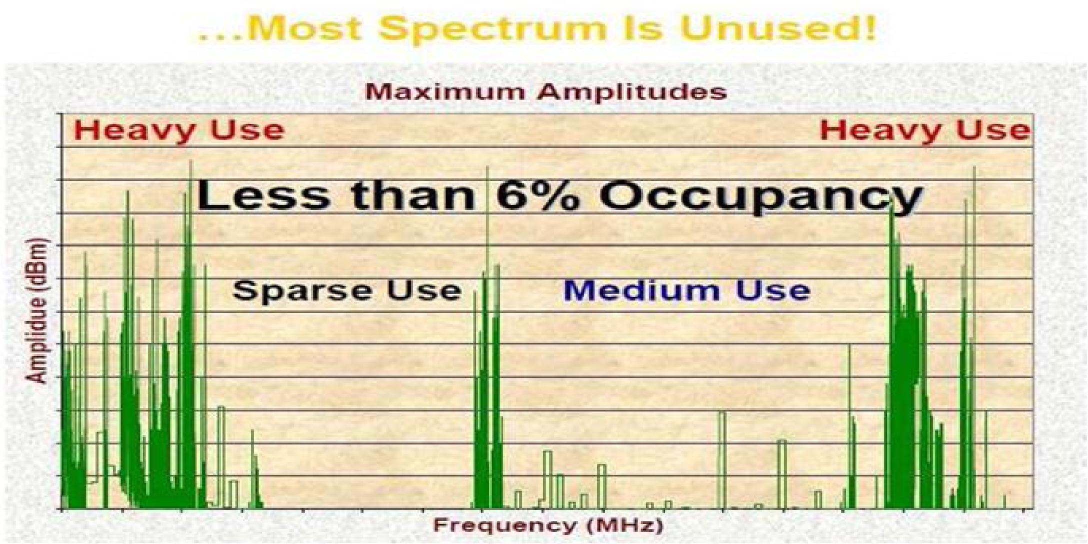

FIGURE 1.2: Spectrum usage by primary and secondary users [8]

1.1.2 Operation

The Cognitive Radio Network (CRN) is based on Software Defined Radio (SDR), equipped with spectrum agile radios. The CR starts its operation by sensing the available spectrum, reconfiguring its radio frequency, switching to the selected unused spectrum and then intelligently utilising this spectrum without interference with the PUs, as shown in Figure 1.3. The four key operations between the primary and secondary users for accessing and utilising the channel(s) are as follows:

1. **Spectrum Sensing:**

   Secondary users sense the primary users' activity and the vacant channel(s) (i.e., available spectrum or spectrum holes or white spaces or unused spectrum) in the licensed channels.

2. **Spectrum Management:**

   Secondary users select reliable channels for the exchange of control and data information.

3. **Spectrum Mobility:**

   Secondary users maintain a seamless communication and switch to other available spectrum bands if a PU returns to its licensed channel(s).

4. **Spectrum Sharing:**

   Secondary users coordinate with each other intelligently over the selected reliable channels, without interference with the PUs.

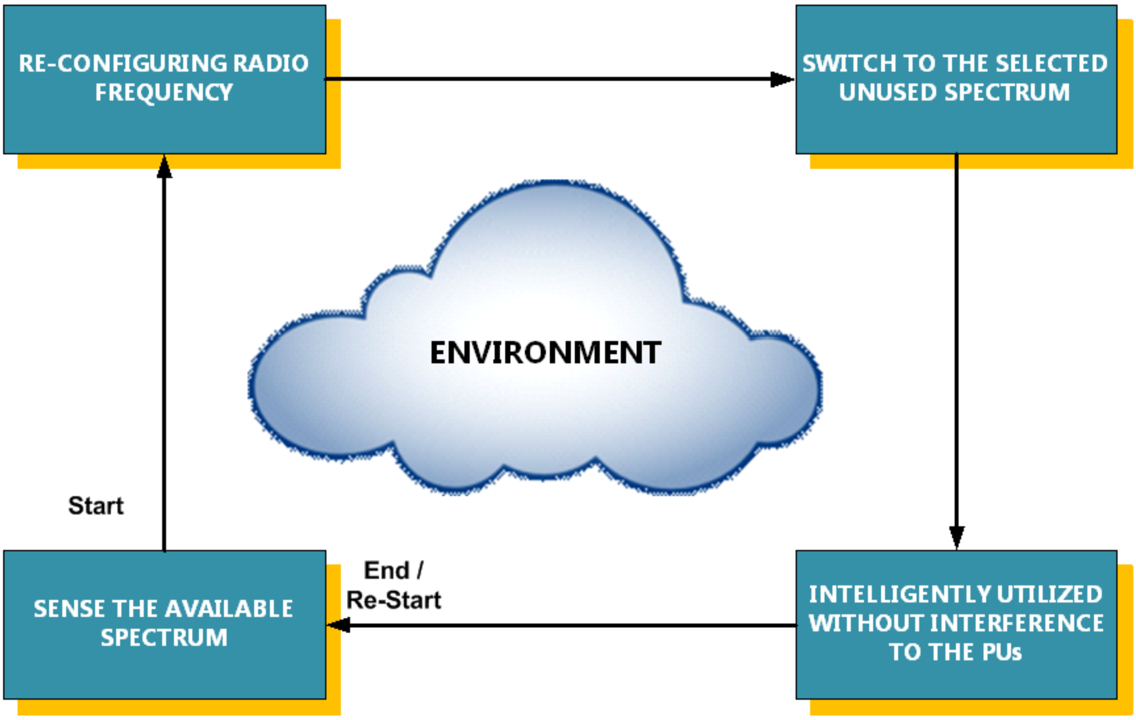

FIGURE 1.3: Cognitive radio operation

The PUs and SUs share the spectrum bands without interference and operate cyclically as shown in Figure 1.3 [10] [11] [12]. SUs detect the "white spaces", configure themselves, and transmit in the white spaces, but discontinue their transmission when the PU returns. Then the SU senses for another available white space to re-start the entire process [13].

1.1.3 Architecture

There are two basic types of CRN: primary networks and secondary networks. A primary network consists of PUs having the right to operate at any time in their licensed bands, such as TV, mobile and microwave bands. The Secondary network consists of SUs to access the licensed spectrum bands without harmful interference with the PUs.

CRNs can be further classified into infrastructure-based and infrastructure-less networks. An infrastructure-based CRN has a central entity, such as a base station in a mobile network or an access point in a Wireless Local Area Network (WLAN), to manage the operation amongst the nodes. However, there is no central entity available in infrastructure-less (de-centralized or adhoc) networks to facilitate communication between CR nodes. Additional coordination is required, which uses more resources to establish communication amongst the SUs and causes additional overheads. It is more challenging for the SU to access the spectrum and manage the communication in an infrastructure-less network as compared with an infrastructure-based network. According to the CRN architecture, multiple entities are required to manage the idle channels [14]. The spectrum owner is responsible for sensing, assigning and managing an infrastructure-based network, but in an infrastructure-less network, CR nodes themselves are required to sense, assign and mange. Therefore, CRAHNs, the infrastructure-less CRNs being considered in this thesis, must sense the unused space(s), assign the unused space(s) to the SU and manage the communication amongst the SUs.

1.1.4 Issues and Challenges

Cognitive radio has been proposed as an emerging and enabling technology, but there are still many open issues and challenges that must be resolved prior to the implementation of the technology. These challenges and issues relate to regulatory authorities, such as the FCC in USA and the Office of Communications (OfCom) in the UK, and the wireless service providers and vendors for the sharing of the licensed spectrum bands. However, if SUs use unlicensed bands, such as the Industrial Scientific and Medical (ISM) bands, then there is no need of this emerging technology because existing wireless applications can use the ISM bands any time without any restrictions.

Some issues relate to the physical layer, such as hardware compliance, including antenna capability and the transmission power rate. Connectivity is another challenge in CRNs, based on the modulation scheme, signal to noise ratio, fading statistics, bit error rate, computational power and battery life. Spectrum sensing for CR applications is also a challenging task which requires an analogue to digital conversion with high range and resolution, advanced signal processors and high sampling rate. Some issues relate to the network layer [15], where routing protocols need to identify the locations of PUs and avoid such routes for the SUs. The network layer is responsible for maintaining the end-to-end routing path for the cognitive traffic. In addition, the network layer is able to distribute the traffic over multiple paths based on the channel conditions and available bandwidth.

Some issues relate to the Medium Access Control (MAC) constraints like frame error rate, data rate, security, inefficient utilisation of the wireless spectrum and selection of random data channels [16] [17]. Another open challenge is related to the random data channel(s) selection in CRAHNs, because of inconsistent PU activity. In this case it is difficult to maintain successful communication between the SUs. The data channel(s) may be available for unequal intervals of time. A random data channel selection in CRAHNs decreases the Probability of Successful Communication (P_{SC}) amongst the SUs due to interference, and/or frequent return of the PU, thus consequently increasing the energy consumption; this becomes more critical when SUs have real time traffic such as voice and disaster information [e.g. text and message(s)] [18] [19] [20] [21] [22] [23]. The frequent return of PUs may require a re-start of the entire process, including spectrum sensing, channel selection and communication over the control and data channels which consumes additional time and has a direct impact on throughput and energy efficiency.

Energy efficiency is another challenge faced by all technologies, especially wireless technology. In particular, the battery life of wireless devices, such as mobile nodes, is limited and the batteries can be difficult to recharge or replace, especially in adhoc networks where there is no central entity available [24] [25]. Reducing energy utilisation has become more demanding in CRAHNs, where SUs consume a lot of energy during the exchange of control and data frames, and re-transmission if the PU returns.

The key task for a network administrator is to secure the wireless network from attackers and hackers. However, an additional security feature is required to secure CR technology due to its adaptive nature. For example, a hacker can pretend to be an SU and join the CR network without authentication and may damage the primary and secondary users and their networks [26].

Based on the above discussion, in this thesis the channel selection strategy, successful data communication and the introduction of the Backup Data Channel (BDC) if PU returns among the SUs, are considered as key features of CRAHNs' MAC layer, as shown in Figure 1.4. Therefore, it is necessary to design a new CR-MAC protocol which handles the challenges discussed above and may provide the solution for selecting reliable data channels and increasing network efficiency. The proposed MAC protocol should cause no interference with the SUs during data communication and should decrease the utilisation of the BDC based on the channel selection strategy. In addition, it is important to reduce the frequency of the re-start process over the control and data channels amongst the SUs, when a PU returns during the communication. To overcome this challenge, the proposed protocol introduces the BDC technique, where selected Data Channels (DCHs) are backup for each other if PU returns on either channel.

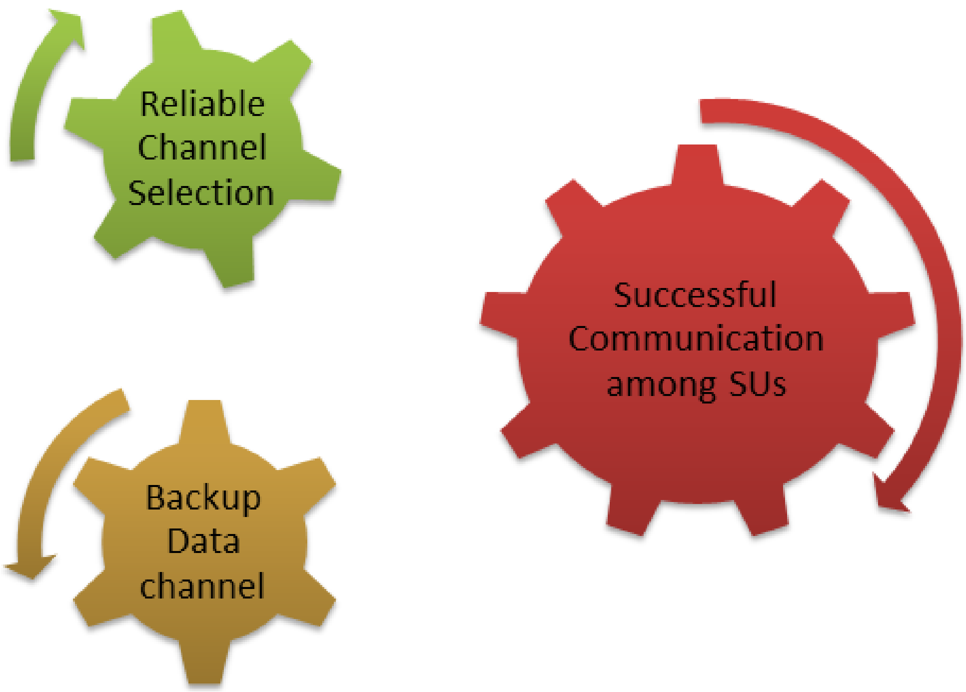

Figure 1.4: Key research challenges (CR-MAC protocols)

1.1.5 Standards and Platforms

A cognitive radio is "a radio that can change its transmitter parameters based on interaction with the environment in which it operates" [27]. A lot of effort has been made from the beginning to develop the standards for CR technology. The Defence Advanced Research Projects Agency (DARPA) develops general policy based radio suitable for cognitive technology under the Next Generation (xG) program using the Extensible Markup Language (XML) [28] [29]. Moreover, the Institute of Electrical and Electronics Engineering (IEEE) 802 community, a regulatory standardisation organisation, has developed two standards, namely IEEE 802.11h and IEEE 802.22, which directly link to CR technology [30] [31] [32]. The problems discussed in the above subsection and other shortcomings have brought the CR technology to the attention of researchers. In addition, other regulatory standardisation organisations such as FCC (USA), Ofcom (UK) and the European Conference of Postal and Telecommunications Administrations (CEPT) have proposed some techniques for SUs to utilise white spaces in the TV band within their particular domains [33]. The regulatory bodies would allow the SUs to utilise the white spaces without interference with the PUs, as the PUs are the licensed users and always have the top priority to utilise their channel(s). A first draft for an infrastructure based CRN has already been proposed in [34] [35]. In addition, industry stakeholders are developing standards for CRNs. For instance, Spectrum Bridge, in partnership with Google and other US based companies [36] and undergoing experimental work in Cambridge, UK and other companies [37], allows trials of a new breed of super Wi-Fi which uses the white space in TV channels.

Apart from these standards, numerous commercial CR platforms and testbeds are available in the market that support partial CR functionality, such as Universal Software Radio Peripheral (USRP) / USRP2 based on GNU radio [38], Wireless open Access Research Platform (WARP) [39], WiNC2R software radio [40], Adapt4 [41], KTS wireless [42], Flex Radio [43] and Orbit [44]. These platforms and testbeds have developed a new technology which allows Next Generation CRs to monitor the activity of the other users in the assigned band without interference and to identify unused spectrum within the network. Moreover, these platforms support high performance CR capabilities such as multiple modulation techniques, Medium Access Control (MAC) and Physical (PHY) functionalities.

1.1.6 Classification of Spectrum Sensing Techniques

The spectrum sensing technique plays a vital role in CRNs due to its capabilities for sensing and awareness of its surroundings. SUs utilise unused spectrum bands adaptively by enabling spectrum sensing and recording the activity of the primary and secondary users. Energy detection, matched filter and cyclostationary feature detection are used to detect the activity of the PUs and SUs. However, there is always a trade-off between accuracy and complexity when selecting the spectrum sensing technique for the CRNs. The details of these spectrum sensing techniques will be discussed in the following chapters.

1.1.7 White Space Geolocation Database

Permitting SUs to access the geographic unused spectrum in the TV band (known as TVWS) has drastically enhanced the effectiveness of the band usage [45]. Since 2008, the FCC has authorised spectrum vendors to build a geographic database based on the unused spectrum for TV broadcasting [46]. Similarly, in the UK, the Analogue TV (ATV) program switched over completely to the Digital TV (DTV) system by 2012. Moreover, it is shown in [47] [48] [49] that the low Ultra High Frequencies (UHF) have good propagation characteristics for the SU and are less harmful for the PUs. Therefore, regulatory authorities have mandated the use of the White Space Database (WSDB) technology for CRNs. The FCC has also authorised Spectrum Bridge as an operator of TVWS, providing the WSDB for the SU to utilise new wireless networking products. The WSDB provides the list of authorised WS with start time, start and stop frequencies of each channel, allowed power level and channel validity time (the time that the SU is allowed to use the channel before having to re-check with the database), based on the user's location for the SU's operation. This list of WS is frequently refreshed to avoid interference [50].

1.1.8 Applications

In spite of the fact that CR technology is in its research stage and is not fully functional and operational for practical purposes, cognitive technology can be deployed for personal and commercial applications within areas such as the telecommunications industry, public safety, disaster management, data messaging, alarm systems, online gaming and health systems for rural and urban areas as discussed in [39] - [36] and [44] - [41]. For example, communication services such as

Orange, British Telecom (BT) and AT&T can use CR technology based on Dynamic Spectrum Access (DSA) to prioritise emergency calls (e.g. 911 in the US and 999 in the UK) over other calls, especially in disaster situations. If each mobile phone has cognitive capability to detect unused spaces and switch to the CR network from its existing network without any cost, then CR technology could benefit mobile phone users by allowing them to enjoy good quality free calls. In addition, mobile phone calls could be switched into the CR network to continue the calls if there was no coverage or poor reception from the mobile operators. Data messages and alarm systems could also utilise the CR technology to transport information within the network and/or outside of the network.

The indoor deployment of femtocells has increased for domestic and commercial users due to their strong indoor coverage and capacity. However, there may be indoor interference present which reduces the signal strength of the femtocells. CR technology could be implemented to overcome the interference problem in the femtocells as discussed in [51].

The Long Term Evolution - Advanced (LTE-A) system requires high downlink bandwidth to obtain maximum throughput. On the other hand, migration of TV channels from analogue to digital system has vacated a large number of TV channels [52]. The LTE-A users could use the TV bands for downloading information, effectively utilising the unused channels by using the cognitive spectrum sharing technique [53].

The number of online gaming users is drastically increasing, but it is required huge investment to increase bandwidth and decrease delays between the players [54]. The online gaming players could employ CR technology and utilise the available spectrum to enjoy gaming in real time. Online chess would be the most attractive application for both cognitive and non cognitive users due to the searching and attempting behaviour of the CR technology.

CR technology could be deployed effectively in the area of E-Health systems for retrieving patient information such as name, date of birth, blood pressure and heart rate. Wireless Personal Area Networks (WPAN) and WLAN can be used effectively for the monitoring of remote patients, especially those living in care homes for the elderly [55]. Worldwide Interoperability for Microwave Access (WiMax) can be effectively used for mobile patients when they are in an ambulance and for remote patient updates in rural areas [56]. Similarly, CR technology is effective in other areas, such as for military purposes, Short Message Service (SMS) and transportation systems [5] [9].

1.2 Problem Statement

The focus of this thesis is to design and build reliable and energy efficient MAC protocol for CRAHNs. As discussed in the above section, the activity of the PU is dynamic in nature for wireless networks, weather the PU returns or not to its licensed channel(s). Therefore, the availability of white space for the SUs in a CRN is also dynamic in nature. In fact, based on the PU activity, the spectrum availability for the SUs is always unreliable and inconsistent. As a result, SUs have to reconfigure their operation from time to time and record the PUs activity behaviour. The existing CR-MAC protocols for adhoc networks select random data channel(s) which may decrease the probability of successful communication among the SU nodes due to interference, and/or the frequent arrival of the PU, consequently increasing the communication time and energy consumption. This becomes more problematic when SUs have critical information to exchange such as voice, data and health related information [6] [7]. In addition, selecting random data channel(s) has a direct impact on throughput and energy efficiency for CRAHNs [20] [24] [23].

The availability of the PU is represented with an ON state and the unavailability of the PU is represented by an OFF state. Coordination among SUs, based on the PU's ON and OFF activity and ownership of the licensed spectrum bands, is difficult to achieve, especially in CRAHNs, where there is no central entity available for controlling the access over DCHs. In this situation, the key issue is how to select the Reliable Data Channels (RDCHs), which play an important role in reliable data communication amongst the SUs. If the PU appears during communication between the SUs, the SUs immediately stop their ongoing communication and restart a new transmission session. Moreover, it is also important to maintain the SU link in the case where the PU returns. In the case of CRAHNs, where channels for data communication are selected randomly, a poor selection of data channel(s) may require the SUs to re-start the entire process again and again due to frequent PU returns, which directly impact the CRN's efficiency in terms of communication time, energy consumption, and network throughput. Therefore, a new CR-MAC protocol is required to overcome the existing shortcomings and to enhance spectrum usability by allowing the SUs to opportunistically access unused or under-utilised radio spectrum. In addition, a new channel selection strategy is required to select data channels with certain criteria, and reduce the overheads of control frames. Moreover, an additional free channel is required to continue the communication if the PU returns, which increases the probability of saving some additional communication time and energy.

1.3 Contribution of the Thesis

The main aim of this research is to design a reliable and energy efficient MAC protocol for CRAHNs. The contributions of this thesis are as follows:

1.3.1 Spectrum Sharing without Interference

As discussed in the previous section, the PUs are the licensed users, and always have first priority to utilise their channel(s). Hence, the first contribution of this thesis is to select the spectrum for the SUs without overlapping or causing interference with the PUs. To overcome overlapping and interference between the SUs and PUs, the author proposed RECR-MAC protocol framework that allows SUs to communicate over the DCH without interference with the PUs.

1.3.2 Exchanging Control Information

Exchange of control information over the Control Channel (CCH) is the primary task in both infrastructure-based and infrastructure-less CRNs. In infrastructure-based networks, a centralised entity such as a base station controls the activity of the SUs over the control channel. However, in the infrastructure-less networks, there is no central entity available to govern the exchanges of control information. The SUs exchange control information over the CCH are responsible for providing information on frame size including data, PU activity, communication duration, and which DCH(s) are to be used. To overcome this challenge, the proposed RECR-MAC protocol is capable to manage the successful exchange of control information over the CCH, and providing information to the SUs for subsequent data communication.

1.3.3 Control Information Overheads

The control information overheads, such as the number of handshakes and the size of the control frames, have the greatest impact on successful and unsuccessful exchange over the control channel.

Therefore, it is strongly believed that reducing the control overheads is an important and complex task in CRAHNs. To overcome this challenge, the RECR-MAC protocol optimises the control frames known as Available Channel List (ACL) and Acknowledgment of ACL (AACL) which reduces the number of handshakes and the size of the control frames. The RECR-MAC protocol framework reduces the number and size of control frames by avoiding unnecessary fields to reduce bandwidth consumption, increase the opportunity to transmit, reduce severe delay to other cognitive nodes contending for the medium, reduce pre-transmission time and increase post-transmission time for subsequent data communication.

1.3.4 Selection of Data Channel(s)

Another important step is to select reliable data channel(s) for successful data communication amongst the SUs. In reality, the technique for selection of a reliable data channel plays a fundamental role in robust data communication. If SUs select random channel(s), there is a lower chance of selecting reliable data channels, which may reduce successful data communication among the SUs. Therefore, another contribution of this thesis is to define reliable channel selection criteria for data communication between the SUs.

1.3.5 Selection of Backup Data Channel(s)

Another challenge is to continue communication over the data channel(s) if the PU returns and / or the channel degrades due to negative acknowledgment, which creates a need for additional time to exchange control information and select data channel(s). The re-start process also consumes additional energy for data frames and introduces delay for disaster networks; ultimately, it reduces the overall throughput of the CRAHN. To overcome this challenge, the RECR-MAC protocol introduces a novel backup data channel technique to continue the communication even if the PU returns on the data channel.

1.3.6 Implementation and Evaluation

Validation of the novel developments described in this thesis would not be possible without the implementation of the protocol and its evaluation against other existing benchmark protocols. Another contribution of this thesis is to develop a CRN model, including primary user activity, in the MATLAB simulation tool. MATLAB is widely used in wireless research, but due to the fact that CR is an emerging area of research, a comprehensive and precise simulation model for CRAHNs is still unavailable. To overcome this, the author has designed and developed a model including PU and SU activities and mobility for SUs if the PUs return during communication. Moreover, the functionality of the proposed protocol is evaluated by comparing it with well known benchmark CR-MAC protocols ([57] [20] [58] [23]) based on adhoc networks.

1.4 Protocol Description

The most important and significant characteristic of the CRAHN is to successfully transmit information amongst the SUs, because SUs do not own the channel(s) and utilise these channels when the PUs are not using the channels. Secondly, it is important to maintain the links between the SUs for data communication if a PU returns to its licensed channel(s) during the communication.

This section describes the proposed RECR-MAC protocol based on DCH selection criteria and BDC. The RECR-MAC protocol is an efficient protocol, in terms of reliability of the DCH selection criteria, communication time, energy utilisation and throughput of the CRAHN. The selection criteria for the reliable data channel(s) are based on multiple factors; initially the reliable channels are selected based on the maximum free time on the DCH, then the channels are given a ranking, which is proportional to the number of positive/negative acknowledgments and history of the DCHs. If more than two DCHs have the same value of ranking during the second, third and subsequent iterations, then the DCHs are selected based on the maximum free time. The priorities of the data channels are assigned as Reliable Data Channel 1 (RDCH 1), RDCH 2, RDCH 3, and RDCH 4 (where RDCH 1 and RDCH 2 have the highest priority, RDCH 3 and RDCH 4 have the next priority and so on). In addition to that, the RECR-MAC protocol guards against interference and overlapping between the PUs and SUs over the DCH by considering channel selection criteria and provides effective and robust data communication within the CRAHN.

According to the best of the author's knowledge, no one has designed and developed an efficient and reliable energy efficient framework and protocol, which select RDCs using selection criteria and uses a BDC simultaneously, and therefore the proposed RECR-MAC protocol forms the main contribution of this thesis, increasing the reliability of the SU's communication, reducing communication time, energy consumption and delay due to the reduction in control channel overheads and re-transmissions and increasing overall network throughput.

1.5 Aim and Objectives

The overall aim of this report is to design and develop a novel "Reliable and Energy Efficient CR Multichannel MAC Protocol for Adhoc Networks" named the RECR-MAC protocol.

The objectives are as follows:

1. To develop a framework for the RECR-MAC protocol for CRAHNs
2. To develop the channel selection strategy, to select the reliable data channel(s) with respect to channel ranking and history of the channel. The ranking of the channel depends on the number of positive acknowledgement(s) (No Re-transmission) and number of negative acknowledgement(s) (Re-transmission).
3. To introduce the BDC, to continue the ongoing process of communication even when the PU returns over the data channel.
4. To evaluate and compare the analytical results returned by the RECR-MAC protocol with those returned by other CR-MAC protocols.
5. To develop a simulation of the RECR-MAC protocol. In addition, to compare the analytical and simulation results for the proposed protocol, in terms of communication time, transmitted energy consumption and throughput with other existing CR-MAC protocols, as a benchmark protocol in the area of CRAHNs.

1.6 Organisation of Thesis

This thesis is arranged into eight chapters as presented in Figure 1.5.

Chapter 1: This chapter discusses the background, operation and architecture of CR technology. In addition, this chapter discusses the commercial platforms and standards along with their applications. Moreover, the problem statement describes the challenges which face researchers and industry in the area of CRNs.

Chapter 2: This chapter provides an in-depth review of existing CR-MAC protocols. The classification model of the CR-MAC protocol is designed based on different aspects of the technology such as spectrum sensing, control and data channel(s) selection criteria, communication time, energy saving mechanisms and throughput of the network. Based on the literature, this chapter gives the motivation to design a novel CR-MAC protocol which overcomes the existing challenges and problems discussed in Chapter 1.

Chapter 3: This chapter presents the model of the proposed RECR-MAC protocol along with its aims and objectives. The flowchart of the proposed protocol consists of four phases and for each phase the operation is discussed thoroughly. At the end of this chapter, the frame format and frame handshaking functionality of the SUs over the control and data channels are described.

Chapter 4: This chapter proposes the framework of the channel selection strategy that the RECR-MAC protocol will use instead of random channel selection. The impact of the proposed channel selection strategy on the communication time between the SUs for the primary and backup data channels is analysed. In addition, the proposed RECR-MAC protocol is analysed and compared with other benchmark CR-MAC protocols based on the channel selection strategy and communication time.

Chapter 5: This chapter discusses the analysis of energy consumed during the transmission of control and data frames, based on the communication time calculated in the chapter 4. Furthermore, analysis of the RECR-MAC protocol throughput will be discussed, based on contributing factors such as channel switching among SUs, transmission probability of SUs, number of DCHs and multiple data rates. This chapter also covers the performance analysis of the RECR-MAC protocol and its comparison with the benchmark CR-MAC protocols for the transmission energy among the SUs and overall throughput of the proposed network.

Chapter 6: This chapter describes the impact of PU activity on communication time of the RECR-MAC and the benchmark CR-MAC protocols. It also covers the impact of PU activity, with and without a backup data channel. The performance of successful data transmission during each simulation run with different data rates and numbers of SUs is discussed in detail. Moreover, comparison of the RECR-MAC protocol and other CR-MAC protocols are discussed in detail based on an implementation of the protocol using the MATLAB simulation tool.

Chapter 7: This chapter introduces the performance optimisation of the RECR-MAC protocol and investigates its operation over the control and data channels, with and without backup data channels. The in-depth functionality of the RECR-MAC protocol will be verified by changing the number of SUs, DCHs, beacon time, and PU ON/OFF activity. It also provides an extensive comparison of the RECR-MAC protocol with other benchmark CR-MAC protocols in terms of communication time over the control and data channels, transmitting energy utilisation, with and without PU returns, and overall network throughput.

Chapter 8: This chapter presents the conclusions and suggested directions for future work.

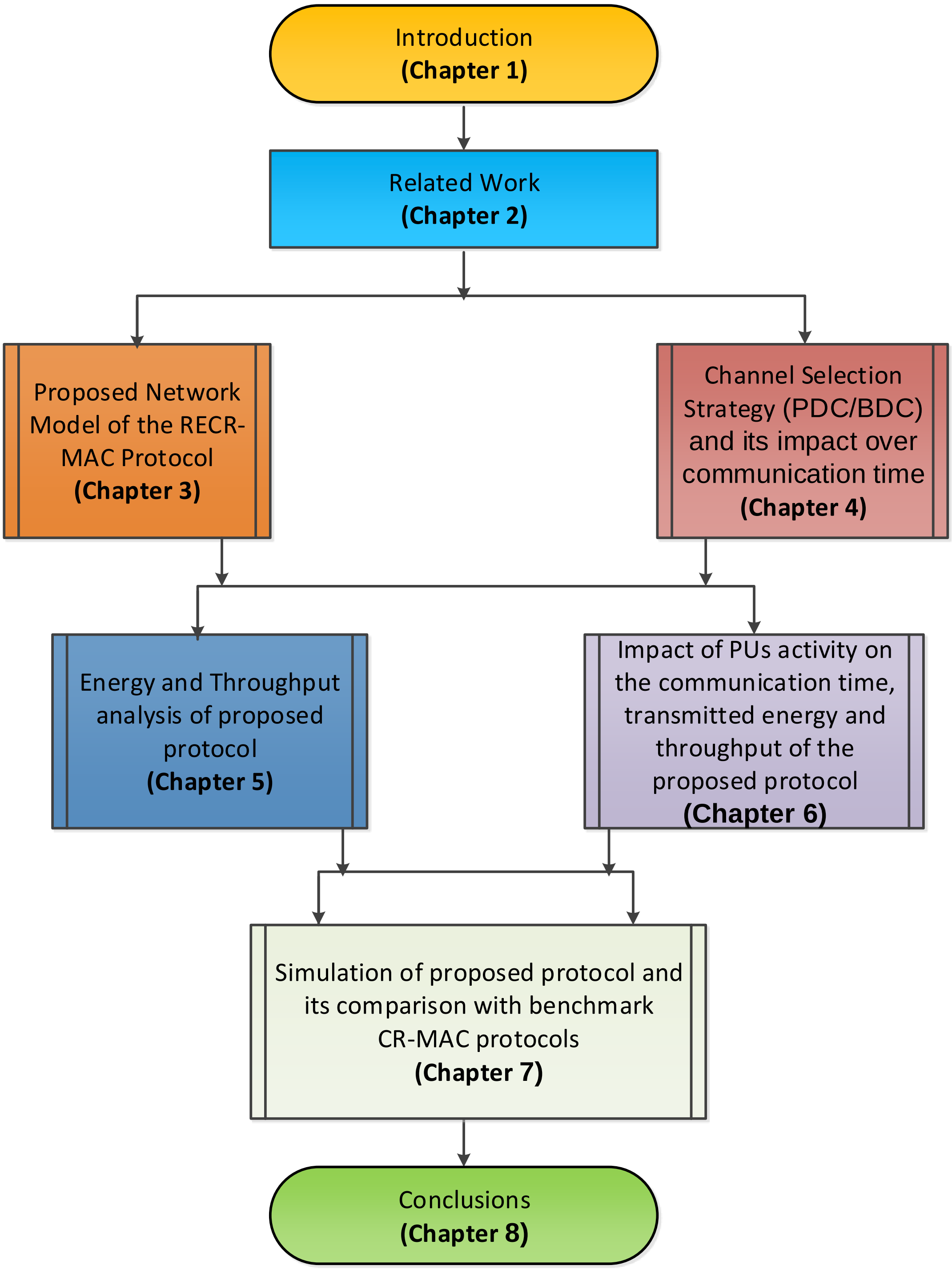

FIGURE 1.5: Flowchart of the thesis

Chapter 2

Related Work

Cognitive radio (CR) technology provides a framework to allow radio devices to access the spectrum dynamically and sense unused spectrum. To utilise spectrum opportunities within licensed spectrum bands, CR nodes have a sensor which helps SUs sense the availability of licensed channel(s). After sensing the licensed spectrum, the SUs create the Free Channel List (FCL) while PUs are not transmitting. The SUs, also known as opportunistic users, use vacant channel(s) opportunistically without interference to the PUs [59] [60]. If the PUs return to the licensed channel(s) being used by the SUs, then the SUs immediately stop their communication and switch to another vacant channel [58] or re-start the entire procedure [61] [62] [63] [64] [65].

Development and advancement in CR technology are based on extensive research on the physical to the network layer [66]. Research of the physical layer focuses on numerous areas including development of SDR, modulation schemes depending on the Orthogonal Frequency-Division Multiple Access (OFDMA) technique, channel characteristics, spectrum sensing and power control. This thesis focuses on the layer above the physical layer, i.e. the MAC layer and related concerns such as selection of the DCH, reliability of data communication and consumption of the communication time and energy in the CRAHNs. Since the commencement of CRNs, various Medium Access Control (MAC) protocols for wireless technologies have been developed. The complexity of designing CRAHN lies in the design of the spectrum sensing function at the physical layer and in ensuring reliable and efficient communication over the DCH without interference to the PU at the MAC layer [67].

The review of the topics of interest given in this chapter follows the categorisation of the CR-MAC protocol as shown in Figure 2.1. The areas to which this research will contribute are marked by a dotted line in Figure 2.1. Section 2.1 discusses the characteristics of the infrastructure and infrastructure-less CR-MAC protocols. Section 2.2 provides an in-depth analysis of the non-dedicated and dedicated control channels and a comparison of the available well-known CRAHNs protocols. Section 2.3 discusses the applications of the single and multiple transceivers for the CRAHNs. Sections 2.4 to 2.7 provide detailed descriptions of the CRAHNs and how CR nodes sense and access the spectrum, utilise the spectrum effectively and switch to BDC if PU returns. Section 2.8 describes the CR-MAC protocols based on communication time, energy consumption and throughput.

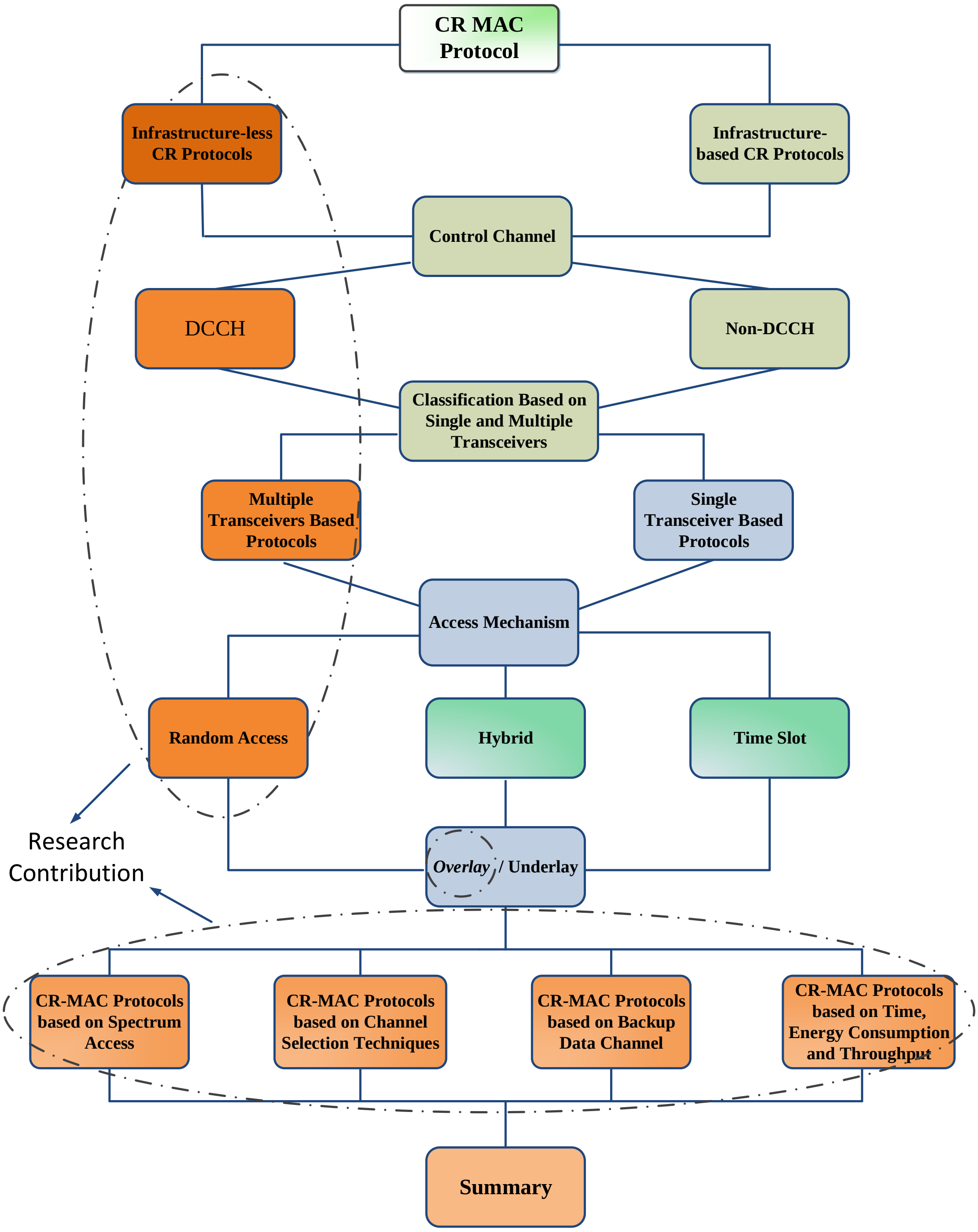

FIGURE 2.1: Classification model of CR-MAC protocols (areas to which this research has contributed are shown within the dotted line)

2.1 Cognitive Radio Medium Access Control Protocols

CR is capable of sensing unoccupied band(s), configuring itself, utilising white space(s) and then establishing its connection over these white space(s) [10]. MAC is the second layer that plays a vital role for the SUs operation to exchange control and spectrum information via CCH (i.e. Dedicated Control Channel (DCCH) and/or Non-DCCH (NDCCH)) and switch to white spaces to communicate with each other [25]. The DCCH must be recognised and available for all SUs to access and utilise the spectrum without interference to the licensed users. Thus, the MAC protocol facilitates the CR nodes' channel access and the addressing mechanisms of the SUs as well as manages the re-configuration based on spectrum sensing. The CR MAC protocol can be further classified according to the following characteristics: infrastructure-based or infrastructure-less; use of DCCH and/or NDCCH; channel access mechanism; in-band or out-of-band channel; underlay or overlay mechanism; synchronous or asynchronous CRNs; dynamic or direct spectrum allocation based; single or multichannel; single or multi-radios; and cooperative or non-cooperative. The next section discusses each category of CR MAC protocol in detail.

2.1.1 Infrastructure-based CR Networks

Infrastructure-based CRN is based on a central entity such as an access point and a base station, which manages the cognitive activities in the network. The central entity is responsible for managing information for spectrum availability, mobility, management, security and cooperation among cognitive nodes in the infrastructure-based networks as shown in Figure 2.2. Cordeiro *et al* [31] has proposed IEEE 802.22, the first worldwide wireless standard for CR, but their applications are restricted to TV channels. Stevenson *et al* [68] has presented an enhanced version of IEEE 802.22 for Wireless Regional Area Networks (WRANs). Brik *et al* [69] has introduced the concept of Dynamic Spectrum Access Protocol (DSAP), to utilise DSAP servers and DSAP relay as centralised entities that coordinate spectrum access requests and permit multi-hop communication between DSAP clients similar to the Dynamic Host Configuration Protocol (DHCP). The centralised CRNs use Frequency Division Multiplexing (FDM) to segregate the spectrum into pre-determined frequency slots for the SUs communication [70]. In addition, the Time Division Multiplexing (TDM) technique is adopted to determine the activity of the PUs and exchange control frames among the server and clients without any channel selection criteria. A point to multi-point CRNs requires two steps for cooperation between primary and secondary users to maximise the coverage and throughput of the SUs [71].

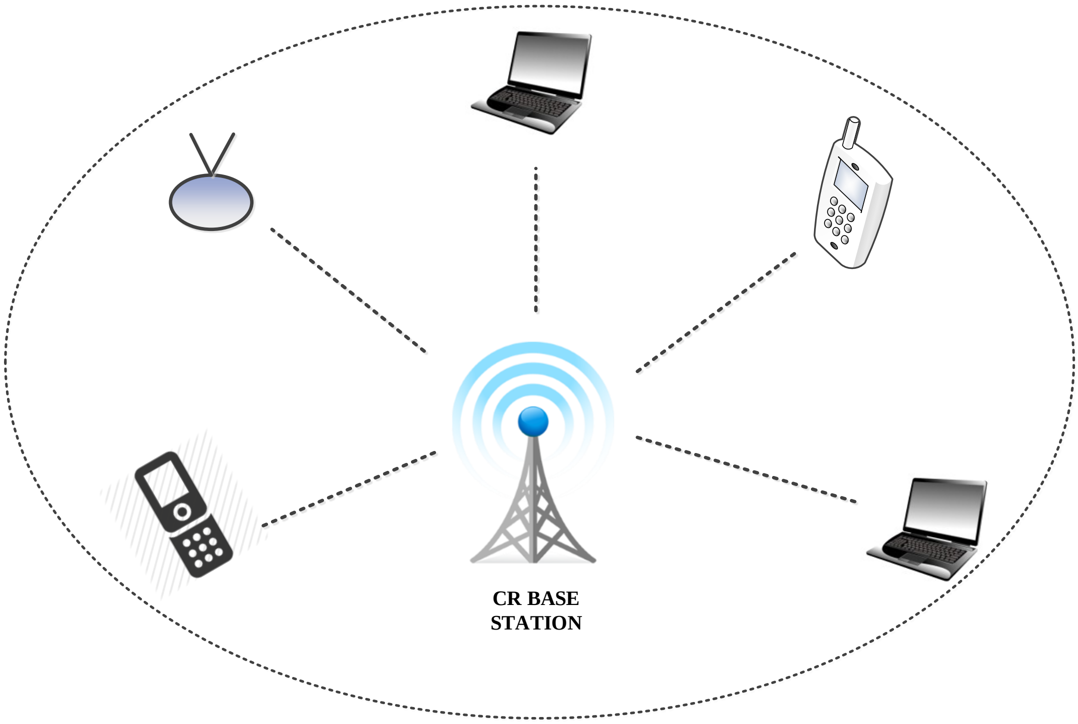

FIGURE 2.2: Infrastructure-based CRN

2.1.2 Infrastructure-less CR Networks

In infrastructure-less CRNs, the SUs can communicate directly with other SUs without a central entity and are responsible for all operations and functionality, as shown in Figure 2.3. SUs can leave and join the system at any moment without interfering with PU activity. Extensive research have been carried out in the area of CRAHNs which addresses multiple issues such as spectrum management, spectrum sharing on control and data channels, synchronisation of nodes, power saving, throughput, data dissemination and emergency message dissemination in vehicular networks [72] [73] [58] [21] [74] [22] [23] [67]. The CRAHNs are categorised on the basis of CCH that can be further classified into DCCH and NDCCH. The following section discusses the characteristics of NDCCH and DCCH.

This thesis focuses on CRAHNs based on DCCH, there is no central entity to govern the information among the SUs, including channel selection, communication time and energy management and throughput of the network. In addition, it is assumed that the CCH is dedicated and always available and reliable for SUs exchanging control information between the CR nodes for the DCHs. The following section discusses the CCH and its classifications for CRAHNs.

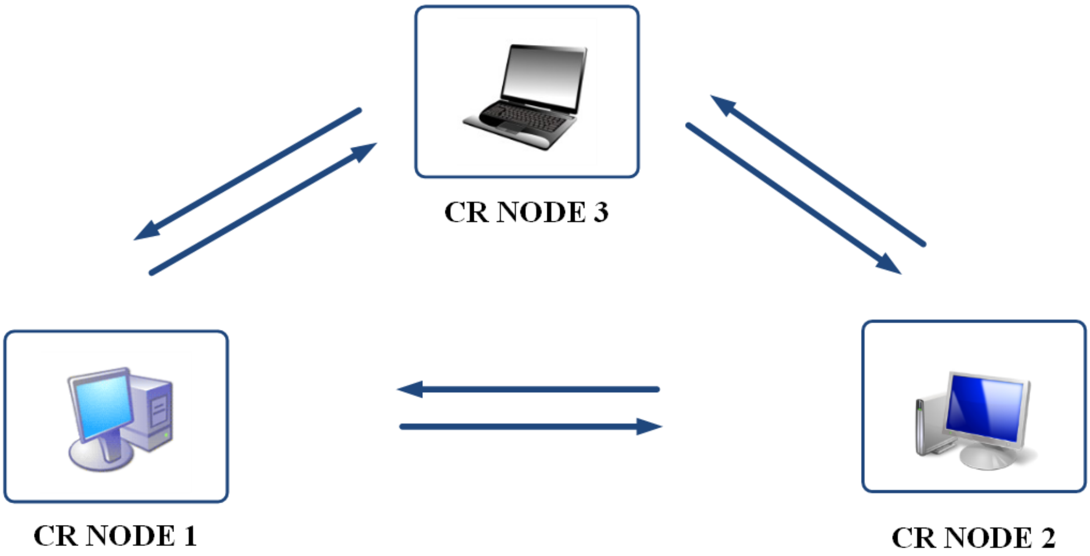

FIGURE 2.3: Infrastructure-less CRN

2.2 Control Channel

As discussed in subsection 2.1.2, the CCH facilitates the SUs' exchange of their preliminary information before switching to DCH in infrastructure-less networks. The CCH can be classified into static and dynamic cases. Under the static mode, the CCH is called DCCH to the SUs or the Industrial Scientific and Medical (ISM) frequency spectrum with a frequency value of 2.4 GHz (IEEE 802.11b/g). In the dynamic case, the SU selects unused licensed channels to exchange control information [75] [23]. The CCH is further classified into two main categories.

2.2.1 Non-Dedicated Control Channel Protocols

In this category, the SU selects and utilises one of the most reliable white spaces as a CCH to exchange all control information before starting the communication. The decentralised Adaptive

MAC (A-MAC) protocol has assumed that NDCCH with N sets of channels utilise unused space effectively [73]. In A-MAC, a SU retains a Channel STatus Table (CSTT) and indexes the channels repeatedly. A-MAC adopted 802.11 Distribution Coordination Function (DCF) spectrum access mechanisms to select the most reliable channel as a CCH among the SUs with high probability to be stable. The channel stability is based on high bandwidth, reliability of the channel, channel condition, and channel usability, but there is no discussion about these parameters in the A-MAC protocol.

The Cognitive MAC (C-MAC) Protocol for Multi-Channel Wireless Networks has adopted the idea of a dynamic Rendezvous Channel (RC) to select the unused time slot and set this channel as a CCH which manages and coordinates all control and data communication [72]. The C-MAC considers simultaneous communication over all available DCHs, where each transmitter has an infinite frame to send to the receiver, as not being a practical approach in the CRAHNs. In addition, this transmission approach wastes network resources, consumes additional time and energy and introduces excess delay.

The Synchronized MAC (SYN-MAC) protocol for CRNs select one of the common free channels to exchange all control information, using 802.11 DCF mechanism, with the neighbours while the rest of the available channels are utilised for data communication [76]. There might be the case that each SU has a choice of more than one common channel between the sender and the receiver. In this case, the SU sender and receiver need to agree on a common available channel which is known as the CCH. SYN-MAC is designed to avoid Denial of Services (DoS) attacks and the multi-channel hidden terminal problem. Concealed terminal problem happens when the SU is listed on a specific channel, but is unable to listen to communications taking place through a different channel. If this problem happens in a multi-channel environment it is referred to as a multi-channel hidden terminal problem.

The efficient discovery and recovery of common control channel in CRAHNs have proposed the important aspects of CRNs are to search, scan and access the CCH and advertise the collected information amongst the SUs [75]. This proposed technique requires at least two CCHs to exchange the information among the SUs based on two level of accessing techniques named as rapid channel accessing and reliable channel accessing.

The Common Control Channel CR-MAC Protocol in a distributed way (DCP-CCC) [77] has proposed the appearance patterns of Primary System (PS) and connectivity of the SUs in the CR networks. SUs are able to detect white holes, which are available for the entire network and have a unique channel ID, and then utilise them effectively. The SU must scan all possible available channels to receive a Common Channel Beacon (CC-BC), which is periodically broadcast by a cluster head. The minimum scanning time for listening to one channel is T_P, to record free channels as well as CC-BC, where there is no PU available during that scanning time. If there is no information about the CC-BC during the scanning time, then the SUs use the Carrier Sense Multiple Access Collision Avoidance (CSMS/CA) process to start sending a Common Channel Invite (CC-IVT) to their neighbours. If a receiver node receives CC-IVT successfully, then it selects common channel for the data communication. There is the possibility that the selected CCH may be occupied by the time the cognitive nodes in the network structure the cluster.

To conclude, the selection of the NDCCH is required for exchanging control information among the SUs, if there are no PU returns. In realistic and practical situations, the return of the PU is unpredictable and it may happen that the PU returns during the exchange of the SUs over the CCH. In such cases, the above articles must always consider backup CCH in their available channel list rather than scan and select new NDCCHs. In research relating to this issue, most of the researchers assumed that the CCH is NDCCH without discussing their selection process and did not go into what would happen if the PU were to return during the communication.

2.2.2 Dedicated Control Channel Protocols

The authors of [57] [20] [58] [24] [78] [25] [23] assume that the CCH is dedicated and is always available for exchanging the control information prior to any data communication. As discussed in Chapter 1, the FCC and other committees report that 70% to 94% of licensed spectrum bands are underutilised in urban rural areas. This means that a whole database of white/free spaces is widely available as discussed in [79]. Based on the FCC's and other related committees' research, it is assumed in this thesis that the CCH is dedicated and that only 30% of the spectrum is occupied most of the time. Another benefit of the DCCH is that it is available 24x7 without any permission and license requirements, although it may vulnerable to a Denial of Service (DoS) attack [80].

The F^2-MAC protocol discuss the issues of efficient channel sensing and its access mechanism for CRNs [81]. F^2-MAC protocol overcomes the problems of channel sensing by using the channel hopping technique and adopt a rendezvous process to access the NDCCH, exchanging control information among the cognitive nodes [82]. Five types of control messages are used in the F^2-MAC protocol. Two categories of control frames are similar to conventional RTS and CTS and are delivered through DCCH. The remaining three additional frames such as Data Channel Idle (DCI), DCI-ACK and Ready-To-Vacate (RTV) are delivered via DCHs. F^2-MAC adopted the proactive channel strategy in which the activity of the PU is predicted and the SU selects the channel based on the prediction. In F^2-MAC, a SU senses the DCHs and transmits the RTV frame and then waits for a certain length of time. The transmission of multiple frames simultaneously over the licensed channels improves the overall throughput of the CRNs but this transmission increases the CCH overheads and consumes additional time and energy.

The Multi-Channel Cognitive MAC Protocol with Efficient Channel Reservation and Collision Avoidance method is based on Backup Channel Reservation Protocol (BCRP-MAC) [18], which includes the information for the BDC in the message of the control frames over the DCCH for the ongoing transmission instead of the sending of additional control packets. BCRP-MAC protocol uses the Duration Identification (DI), which decides the released time of the occupied channel. In addition, the BDC is used to continue the data communication if the PU returns, which reduces the additional overheads over the CCH and improves the network throughput. However, each cognitive node maintains the sensed DCH for data communication without considering the reliable selection of the DCHs.

The Cognitive Radio Enabled Multi-Channel MAC for CRNs (CREAM-MAC) protocol adopts four-way handshaking over the CCH for the selection of DCHs under the assumption that the CCH is dedicated, reliable and always available [23]. The CREAM-MAC incorporates the spectrum sensing at the physical layer using Markov queuing models and packet scheduling at the MAC layer. CREAM-MAC also assumes that a CCH has been selected and agreed by all SUs before starting its operation. In addition, each cognitive node is equipped with a transceiver with multiple sensors that seizes the opportunity for the SUs with acceptable interference to the PUs.

However, CREAM-MAC selects the random DCHs for the communication and restarts the entire process if the PU returns.

The Dynamic Spectrum Access MAC protocol based on CR for QoS support (DSA-MAC) has adopted multiple transceivers but is restricted to ZigBee channels from 0 to 26 [20]. Channel 0 is dedicated to control information while the remaining channels are dedicated to data communication. The DSA-MAC protocol uses a hello message which contains a Spectrum Status Table (SST), such as Channel ID and Signal to Interference plus Noise ratio (SINR) of the channel, to enhance the spectrum sharing. In addition, the SU exchanges the hello message over the DCCH and the data message over the DCH using six way handshaking, which is an additional overhead when compared to four way handshaking. However, DSA-MAC restarts its entire process to select control and data channels if the PU returns during the communication.

Energy Efficient Cognitive Radio MAC Protocol for Ad-Hoc Networks (EECR-MAC) has considered DCCH with a single transceiver using two-way handshakes over the CCH [21]. The EECR-MAC uses the frame aggregation and BDC schemes simultaneously to reduce communication overheads over the CCH. The availability of a BDC has allowed nodes to avoid re-negotiating the channel in case of interference from the PU, while frame aggregation further reduces the overall communication overheads. However, the random DCH selection process was adopted for data communication which may reduce the network performance.

The Cognitive Radio Multichannel MAC protocols for wireless Ad-Hoc networks (CRM-MAC) sensing at the physical layer and scheduling the packet at the MAC layer [25]. In CRM-MAC protocol, each SU has two transceivers. One transceiver is dedicated for data communication, while the other transceiver is used to periodically sense the activity of the other nodes and utilise the unused channels randomly. CRM-MAC has adopted a random DCH selection technique and is unable to continue the communication if the PU returns.

In TDMA based Energy Efficient Multichannel MAC protocol for CRAHNs (ECR-MAC), where each SU is equipped with a single transmitter/receiver to scan several channels [24]. One of the scanned channels is always used as a DCCH to exchange control information and the rest of the channels are available for data communication. The pair of SUs can only communicate if both cognitive nodes select the same channel and are within transmission range of each other. However, a main disadvantage of the ECR-MAC protocol is synchronisation, where the channel timeslot negotiations are completed prior to channel sensing, which may be affected by the out-of-date spectrum sensing results. In addition, the ECR-MAC is unable to continue the communication over the selected DCH if the PU returns.

The opportunistic Spectrum access WITh backup CHannel (SWITCH) is proposed by [58] based on multichannel MAC protocol for CRAHNs, where each SU is equipped with two transceivers, one transceiver is assigned for the DCCH for exchanges control information and other transceiver is dedicated for DCHs. SWITCH is assumed to have two types of DCHs named C1 and C2. The C1 channels operate in the licensed spectrum when the PU does not occupy the channel, and the C2 channels operate in the unlicensed spectrum. The C2 channels are also used as BDC in cases of PU returns over the C1 channels. If there is no unused channel available among the C1, then channel C2 among the PUs having least activity is selected as a BDC. In SWITCH, the allocation of the data structure consists of two types of spectrum, the Free Channel List (FCL) which contains the record of free channels within the transmission range, and the Neighbours Channel List (NCL) where each node keeps a database of channels occupied by neighbours. SWITCH has adopted RT-S/CTS control frames, but a new packet called Notification-To-Reserve (NTR), which has a packet format similar to CTS, is added. The NTR packet is transmitted to its neighbours only when the PDC and/or BDC is transmitted by the RTS control information. However, SWITCH uses two ways (RTS/CTS) or three ways (RTS/CTS/NTR) handshaking over the DCCH to select the DCHs depending on the channel availability in the TX/RX sides and the activity of the PUs, SUs and Classical Users. The PUs operate over the unlicensed bands such as ISM bands and Classical Users operate over the licensed bands. The SWITCH protocol adopted inefficient channel selection criteria and the BDC. The details will be discussed in the following chapters.

The MAC protocol for Opportunistic Spectrum Access in Cognitive Radio Networks (OSA-MAC) specifying the DCCH, which is available all the time (i.e., this DCCH may be owned by the secondary service provider), to exchange all control information and to negotiate the channel for data transmission using four way handshaking [78]. The OSA-MAC protocol divides the time into the number of beacon intervals and all SUs are synchronised periodically. In addition, the OSA-MAC incorporates the spectrum sensing capabilities but must vacate the channel to minimise collision when the PU returns over the licensed channel. In OSA-MAC, saturation throughput is analysed under the assumption that the SUs always have data for transmission between the cognitive nodes. However, OSA-MAC selects a random DCH for communication.

The TDMA based Reactive Multi-Channel MAC for Opportunistic Spectrum Access (RMC-MAC) protocol with N number of SUs is required an N number of licensed channels [57]. The SUs exchange their control packets through a single DCCH and their data communication over the multiple DCHs. The RMC-MAC protocol proposes an extra period called Reactive Sensing Period (RSP) along with a contention period, sensing period and data transmission period to facilitate the PU detection over the data channel based on the threshold level of the SINR level. Moreover, the RMC-MAC provides the alternate solution for the active SUs switch to another DCH based on the ACL (SU) list if the PU returns to the licensed data channel(s). If there is no available channel in the ACL (SU) list, then the SU terminates its communication and looks for available new channels to restart the process.

The Opportunistic Cognitive MAC (OC-MAC) protocol selects a DCH from the FCL in and exchanged control information by using three way handshakes via DCCH [83]. Moreover, the SUs selected the channel(s) having low PU occupancy for the data communication which reduces the fair utilisation opportunity for other unused channels. The Acknowledgment (ACK) signal is used to confirm the data transmission over the DCH. The OC-MAC protocol predicts the length of the unused space instead of the exact duration when PU is not utilising the licensed spectrum. The predication of the spectrum hole is criticised because it neither discusses the spectrum access technique nor provide the exact duration of the time among the SUs for data communication.

To summarise, the protocols discussed in this subsection do not include an explanation of how the CCH was selected. The benefit of the DCCH is that it is available all the time without any permission and license requirements and SUs can exchange information over the DCCH and switch to the DCH for their communication. The protocols also assume that the CCH is dedicated and always available for exchanging control information prior to any data communication to achieve successful communication among SUs, thus saving energy and giving a high throughput. There is always a tradeoff among multiple factors in the development of new protocols including the DCCH, NDCCH, DCH, reliability, energy efficiency, delay, throughput, security, cost, and BDC. One of the objectives of this thesis is to design a protocol whose demerits do not degrade the reliability and efficiency of the proposed protocol.

2.3 Classification Based on Single and Multiple Transceivers

The CR-MAC protocols can be classified on the basis of the number of transceiver(s)/radio(s) used. A number of protocols have been proposed in the following subsections that use single and multiple transceivers for the CRNs.

2.3.1 Single Transceiver Based Protocols

With a single transceiver, the SU is unable to listen and sense the activities over the CCH and exchange information over the DCH at the same time. Therefore, it is assumed in the ECR-MAC protocol that each SU is either stationary or moving very slowly and that it transmits at a fixed transmission power [24]. In addition, each SU has a transceiver. The key idea of the ECR-MAC is to divide the time into fixed intervals using beacons with each beacon interval consisting of an Adhoc Traffic Indication Message (ATIM). During the ATIM window, the CCH (i.e. DCCH) is used for beaconing and exchanging control information for the data communication. However, the ECR-MAC channel negotiation is done before channel sensing which may not provide updated information on the unused channel(s).

The Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in CRNs, where each SU has an antenna which attempts to find as many unused spectrums as possible; however, the antennae may be tuned to a specific group of repeated licensed channels and thus overlook the opportunity of picking up new joining licensed channels [62]. In addition, equipping each SU with a single antenna would make it unable to manage the PUs return in a timely manner, which may introduce collision, interference and traditional hidden terminal problems.

The C-MAC protocol [72] is employed the idea of a Rendezvous Channel (RC). The concept of RC is to coordinate cognitive nodes over the different CCH to exchange control information. The C-MAC protocol is Ad-Hoc in nature and is operated over multiple channels which significantly increase the capacity of the wireless networks even though each cognitive node only occupies one

DCH at a time [84]. In C-MAC, each channel is logically divided into super-frames, which contain a slotted Beaconing Period (BP) for SUs to determine the DCH by exchanging control information. In addition, the time is divided into multiple slots for control and data channels. Thus, the C-MAC is a time slotted protocol, which requires global synchronisation among the SUs. However, each SU transmits a Beacon Frame (BF) in an assigned beacon slot during the BP, which may help to solve the hidden node problem and resolve the mobility among the SUs.

To conclude, the SU with a single transceiver is unable to listen and sense the PUs and other SUs activities over the CCH and DCH at the same time. When the SU listens on a specific channel, it may not hear the on-going communication to another channel(s) due to its half duplex nature, which causes hidden terminal problems. In addition, the protocols with a single transceiver do not work effectively in a multi-channel environment where SUs can dynamically switch to the DCHs if the PU returns. The single transceiver is a cost effective solution, utilising less energy when compared to multiple transceivers, but having a lower spectrum efficiency and poorer sensing accuracy for the CRAHNs.

2.3.2 Multiple Transceivers Based Protocols

The design of a multi-channel MAC protocol is significantly simplified by using multiple transceivers that almost solve the challenges of the single transceivers protocols such as the hidden terminal problem, connectivity and channel switching. In this subsection, it is discussed that SUs with multiple transceivers are able to tune and access different channels simultaneously, which improves the overall network throughput.

The DSA-MAC protocol has multiple half-duplex transceivers to access multiple channels simultaneously. The concept of the Multiple-Input Multiple-Output (MIMO) is proposed, which improves network throughput and QoS. It periodically sends a hello message over the CCH to enable the cooperative detection and negotiation process among the cognitive nodes for the data channels [20].

The SWITCH protocol is proposed two transceivers. The first transceiver is dedicated to the DCCH and the other transceiver is dedicated to data communication from any of the available channels with SDR capabilities. The SWITCH protocol achieves cooperation and coordination between the two transceivers, employed by each SU, which are necessary to sense the unused DCHs and to share the sensing information received during sensing among the SUs [58].

The A-MAC protocol is equipped with multiple transceivers where one transceiver is devoted for CCH and the others are used for DCH. In the A-MAC, each SU maintains a CSTT and indexes them frequently. In addition, the A-MAC protocol switches into the dual mode and utilises the BDC when the channel condition is not good and is below the threshold value, hence it increases the throughput of the cognitive networks [73].

The Efficient Channel Sensing and Access Mechanism for CRNs (F^2-MAC) is based on multiple transceivers which provide a fast and fair media access control mechanism [81]. Each SU can utilise multiple DCHs simultaneously, which reduces the communication time and improves the network throughput. In addition, F^2-MAC has achieved fairness in both sensing time and throughput of the network.

The Dynamic Open Spectrum Sharing MAC protocol (DOSS-MAC) is used multiple transceivers (minimum three transceivers) to provide a scalable and real time spectrum allocation solution [85]. In DOSS, there are three categories of spectrums, namely the channel bands for channel negotiation, data bands for transmitting data and busy tone bands for elevating the busy tone signal to solve exposed and hidden terminal problems [86].

The protocol named Dynamic Private Channel (DPC) is proposed cognitive node with multiple transceivers [87]. In addition, the number of transceivers is equal to the number of channels. One transceiver is always dedicated to the CCH for exchanging control information; while the other transceivers are dedicated to DCHs. The DPC provides the solution to the multi-channel hidden terminal problem by employing multiple transceivers.

The Multi-Channel MAC protocol is assumed multiple transceivers equal in number to the number of available DCHs [88]. The selection process of the channel is called soft channel reservation as, when multiple idle channels are available, the last successful channel is considered to be the best channel for data communication.

In [89], the enhanced channel selection strategy describes the selection of the best DCH is based on the power level sensed at the transmitter side. In contrast, the Receiver Based Channel Selection (RBCS) technique is proposed the selection of the best channel based on the SINR at the receiver side [90]. Similarly, the main objective of the Power Saving Multi-Radio-Multi-Channel MAC (PSM-MMAC) protocol [91] is to reduce the use of power during multi-channel operation. This PSM-MMAC protocol is extremely useful in light of the fact that some cognitive nodes are powered by battery.

To conclude, the SU with multiple transceivers solves the challenges of single transceiver protocols such as the ones posed by the hidden terminal problem, multichannel hidden terminal problem, improved sensing accuracy, better spectrum efficiency, connectivity and channel switching, but it increases the cost of the network.

2.4 Spectrum Sensing Techniques

The spectrum sensing and accessing techniques play a vital role in the CRAHNs based on DSA networks. In spectrum sensing, the SUs gather the information regarding spectrum usage and the presence and returns of the PUs, through the physical layer. To improve the detection threshold, three approaches to detect the signal energy were demonstrated in [92][93][94]: matched filter detection, energy detection and cyclostationary feature detections. Matched filter detection is an optimal detection technique with low computational cost, but it requires prior knowledge of the PUs. Cyclostationary detection needs partial knowledge of the PUs but comes at high computational cost. In contrast, the energy detection technique requires a short sensing time and is of low complexity. Additionally, it does not require prior information of the PUs. When selecting a sensing method, some trade-offs should be considered with respect to hardware and SU requirements, such as whether the sensing time is long or short and whether prior knowledge of the PU is required. The energy detection technique is useful during the initialisation of the activity of the protocol because the implementation is simple and efficient when compared to other techniques. In addition, it does not need prior information of the PUs signal features, which is not usually known by the SUs. The energy detection technique would be unable to detect the return of the

PU during the communication of the SUs over the DCH because of the high transmitted energy of the SU. Therefore, the cyclostationary technique is able to differentiate the PU and SU signals and signal the transmitting SUs to stop the communication on that DCH and switch to the BDC. The features of energy detection and cyclostationary techniques are nearer to the properties of the proposed CR-MAC protocol. However, the SUs' access of the geographic unused spectrum in the TV band (known as TVWS) has drastically enhanced the effectiveness of the band usage [45]. Since 2008, the FCC has authorised spectrum vendors to build a geographic database based on the unused spectrum of TV broadcasting [46].

To conclude, in this study, the energy detection technique is assumed to sense the activity of the PUs before starting the communication over the DCH and the cysclostionary technique is assumed during the exchange of the data frames over the DCHs.

2.5 Spectrum Access Techniques

Due to the conventional wireless nature of the CR, the spectrum access mechanism is categorised into three approaches: time slotted, random access and hybrid access. SUs access the spectrum to transmit data when the spectrum is unused and vacate these unused spaces immediately if the PU returns. In the time slotted access mechanism, each SU can only communicate in its particular time slots. Each time slot has a listening period where SUs are synchronised and a communicating period for the exchange of control and data frames. The TDMA technique is used to access CCH to exchange FCL or to transmit data packets in DCH. In [72] [24] [76] [95] [96] [23], the protocols have divided the channels into a fixed or different length of beacon intervals and each beacon interval has a sensing window for sensing the spectrum and communication window for data communication. During the sensing period, cognitive nodes exchange information, and carry out channel negotiation and synchronisation, which handles the hidden node problem, mobility and medium reservation, and enables data transmission during the communication window. The limitation of this technique is that it requires a central entity to manage synchronisation in wider networks.

In the Random Access CR MAC technique, each SU uses CSMA/CA, competes for the medium to exchange control frames on CCH and then switches to the DCH for data communication. In

[97] [98] [59] [85] [99], the cognitive MAC protocols have employed a conventional listen before transmission strategy where each node can sense the carrier before transmission. If the CCH is sensed to be idle, then the sender SU transmits the RTS frame to the SU on the receiver side over the CCH and then the receiver SU replies with the CTS frame to the sender side of the SU. If the CTS packet is received successfully, the transceiver switches to the DCH. Data packets can be transmitted on the DCH followed by an ACK message as shown in Figure 2.4.

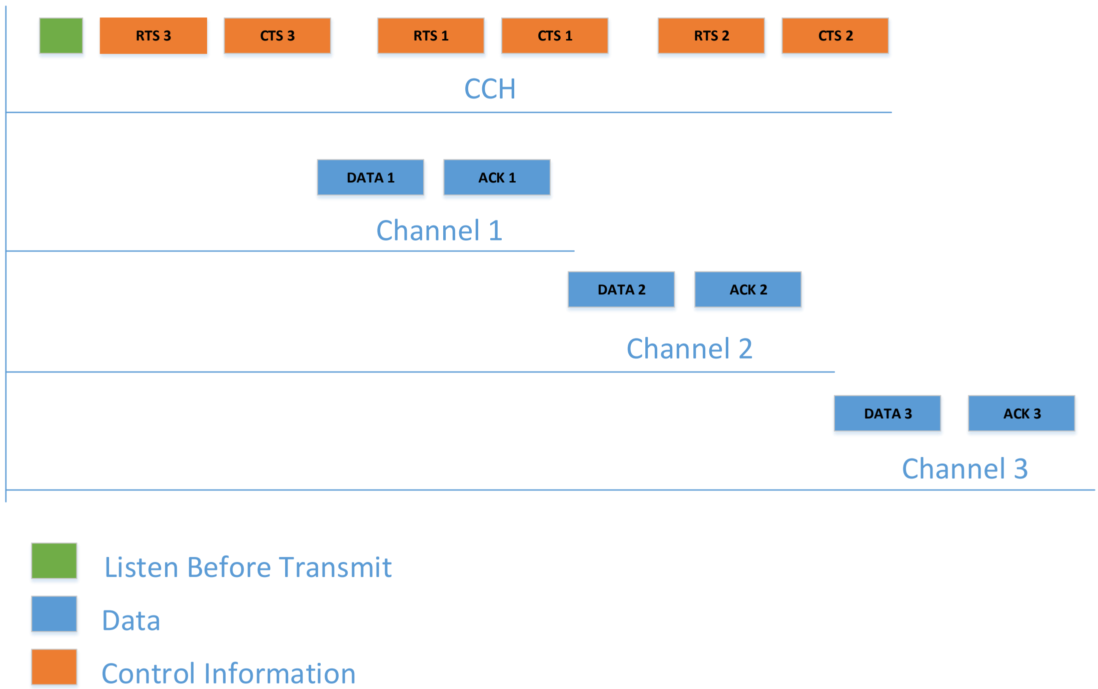

Figure 2.4: Flow of control and data information in the random access CR MAC protocol

Hybrid access MAC uses time slotted and random access techniques simultaneously, where control signals among SUs are synchronised via time slots and data transmission occurs through the random channel access, as discussed in [100][101]. The major drawback in these protocols is the usage of fixed duration time slots, but the length of the time slots varies when nodes join and leave the network.

To conclude, the time slotted technique requires a central entity to manage synchronisation in cognitive networks. In the Random Access technique, each SU competes for the medium to exchange control frames over the CCH and then switches to the DCH for data communication. In this study, the proposed CR-MAC protocol functionality is based on the Random Access mechanism.

The hybrid access mechanism uses the time slots and random access methods simultaneously, but discussion of these methods does not fall within the scope of this thesis.

2.6 Channel Selection Process

In the CRNs, the selection of the control and data channels is the most important factor for the SUs. The SUs need to select the CCH and DCH for the exchange of control and data information. If the PU returns during the communication, the SU pauses the communication and pursues other available DCHs to resume the communication or re-start the entire process. There are a number of channel selection process, which are discussed in [102] [103] [104] [90] [76] [105] [89] [88] [106] [107] [91] [108] [65] for CRNs with and without selection criteria. The channel selection without any criteria is known as random channel selection. The SUs usually assume that the selected channels are equally good, but in fact, the selected channels could be heavily used by PUs. This frequent interval of PUs over the channels disrupts the communication of PUs and SUs. Therefore, the communication performance may be drastically degraded due to frequent channel switching. On the other hand, the SUs selection of channels with certain criteria is known as channel selection process. The prediction of the availability of the future spectrum band helps the SUs to switch to the best channel without or with the minimal appearance of the PU. The SUs must have the ability to decide whether to switch to the channel or not, with no or minimal interference to the PUs. These channel selection approaches are proposed to achieve multiple goals such as channel switching time minimisation, energy saving, throughput optimisation and maximisation, minimisation of the channel switching time from control to data channel, maximisation of the channel utilisation, power allocation, SINR, data rate, packet scheduling, and load balancing [109][110].

The CREAM-MAC protocol [23] integrates cooperative sequential spectrum sensing at the physical layer to increase sensing time and reduce collision and packet scheduling at the MAC layer over the wireless DSA network. In [20], the DSA-MAC protocol obtains the SINR of each channel through the energy detection technique, stores it in a Spectrum Status Table (SST) and selects the DCH based on channel ID and SINR, which increases network throughput. In addition, to improve the spectrum sharing among the cognitive nodes, a hello message, which includes the information about SST over the CCH, is introduced and updated periodically, with ACK-hello being the acknowledgment after the successful communication via the DCH.

In [19], SUs select the DCH having the highest successful transmission probability to send packets based on the channel statistics. However, the delivery of the channel status list and sensed channel list needs additional handshaking which increases the overheads, the computational complexity and energy consumption and decreases network throughput. In [73], the criterion of selection of the DCH is based on the channel ranking and channel conditions. A channel which has more likelihood of stability is considered to be a highly ranked channel for data communication between the cognitive nodes. The OC-MAC protocol is a synchronized cross-layer protocol, which selects the DCH based on the high data rate to increase the network throughput. The OC-MAC is capable of predicting the length of white spaces, but it has adopted an inefficient spectrum access technique [83]. In [111], the network throughput is improved by scheduling the transmission of the CR nodes. In [112], the numerical model for channel reservation is proposed to demonstrate that the DCH reservation technique improves the number of successful transmissions, which extensively improves network throughput, but the implementation process and its specification are not discussed.

To summarise, this section provides a brief literature review related to channel selection strategies and their importance in the CRNs. Furthermore, the channel selection strategies play a vital role in efficient and successful data communication, especially when there is no central entity that helps cognitive nodes in their channel selection decision.

2.7 Backup Data Channel(s)

In CRNs, the PUs have precedence in accessing the licensed spectrum. The SUs opportunistically share the licensed spectrum without interference to the PUs but the SUs must vacate the occupied DCH if the PUs return to their licensed spectrum bands. The most critical task in the CRNs is sustaining the DCH, especially when there is channel degradation due to interferences or PU arrivals over the DCH during the data communication. The PU returns and channel degradation require the SUs to restart the entire selection process, including the process for control and data communication, which increases communication time, energy consumption, collision and delay and decreases the network throughput. Therefore, the BDC and the Backup Control Channel (BCCH) are reserved to reconstruct and maintain the SU link just in case that the PU returns and/or when the channel is degraded due to interferences. In [18], the efficient multiple DCH with BCRP-MAC is introduced the reserved random BDC to reconstruct and maintain a backup link if the PU returns to the licensed band, which improved the network throughput. In addition, each cognitive node maintains the sensed data channel list for data communication and selects a random data channel without considering the "reliable selection of the data channel(s)" based on selecting parameters such as SINR, available time and quality of the channel.

In [21], the EECR-MAC using BDC and frame aggregation technique are adopted to reduce communication overhead. Moreover, the availability of the BDC has allowed nodes to avoid re-negotiating over the CCH in case of interference from the PU, which reduces the overall communication overheads. In [58], the opportunistic SWITCH protocol has adopted the idea of BDC and employed it to make the SU extremely robust in cases of the return of the PUs which increases the network throughput. In addition, the SWITCH protocol is considered unlicensed and licensed spectrum bands to utilize as a BDC. In [73], the A-MAC protocol uses the BDC if the primary channel quality degrades, thus maximising the network throughput. In [113], the Opportunistic Spectrum Access with Backup channel (OSAB-MAC) protocol is introduced the BDC to reduce the spectrum handoff in the CRAHNs. The licensed channels will be used as operating channels and the unlicensed channels will be used as BDC if the PU returns, hence it also improves the network throughput. In [114], the Dynamic Decentralized Hybrid MAC (DDH-MAC) protocol have adopted the BCCH instead of the BDC. Each node consists of two transceivers, thus achieving a lower pre-transmission time over the CCH. In addition, DDH-MAC protocol uses CCCH and non-CCCH unlike other cognitive MAC protocols. If PU returns over the DCH during the data communication, the DDH-MAC starts re-negotiation for the DCH, which consumes additional time and energy and reduces network throughput.

To summarise, the concept of BDC is introduced to minimise the overheads over the control and data channels and maintains the SUs' communication even when the channel condition degrades and/or PU returns to its licensed channels.

2.8 Time, Energy Consumption and Throughput

The studies reviewed in Sections 2.4 and 2.5 have clearly discussed the spectrum sensing and have addressed its access techniques and how to select the control and data channels. In addition, these sections adopt multiple spectrum access techniques, such as time slotted and random and hybrid access to achieve higher network throughput and to save energy. For example, the CREAM-MAC protocol [23] introduces the integrated cooperative sequential spectrum sensing at the physical layer to improve the sensing time on CCH, reducing collisions at the MAC layer and thus improving network throughput. In addition, the ECR-MAC protocol [24] suggests the TDMA technique, which saves energy and increases aggregate throughput of the CRNs, but introduces a small window at the beginning of each interval which increases collision and additional sensing time among the CR users.

Section 2.6 discussed the channel selection processes and their performance with and without PU returns during the communication over the DCH. In addition, multiple channel selection techniques are proposed to select a CCH, either DCCH and/or NDCCH, which increases the overall throughput of the network. It reduces energy consumption and increases the reliability of the data communication. For example, the DSA-MAC protocol [20] selects the DCH based on channel ID and SINR, which increases network throughput. In [19], the CR-MAC protocol with statistical channel allocation selects the DCH that has the highest successful transmission probability to send packets based on the channel statistics which increases the network throughput.

Section 2.7 discussed the BDC, which allows SUs to continue the communication without re-negotiating on the CCH, which reduces additional overhead if the PU returns. These factors have a direct impact on the performance of the CRNs; specifically, they affect communication time, energy and throughput. Moreover, the authors of this section reserve the BDC and the BCCH to reconstruct and maintain the SU link when the PU returns and/or when the channel is degraded due to interferences. In [18], the BCRP-MAC protocol reserves random BDC which reconstructs and maintains the backup link if the PU returns to the licensed spectrum band, thus improving network throughput. In [58], the SWITCH protocol operates over licensed and unlicensed spectrums. SWITCH uses the idea of the BDC and employs it to make the SU tremendously robust when it comes to the return of the PUs, which tremendously increases the network throughput.

To summarise, the channel selection technique with criteria leads to the selection of a reliable DCHs which increases the probability of the successful communication and reduces re-transmission among the SUs. In addition, the introduction of the BDC reduces the overheads among the SUs, saves on communication time and energy and increases the network throughput of the CRAHNs.

2.9 Summary and Contributions

This chapter presented a number of CR-MAC protocols and their parameters with their limits and constraints. All CR-MAC protocols exchange their control frames, such as ACL/AACL, RTS/CTS and ACK over the DCCH and non-DCCH. In this study, it is assumed that SUs exchange control information over the DCCH which is always reliable and available and may be owned by the service provider, as assumed in [24] [78] [21] [23]. The control information is a pre-requisite for all CR nodes before switching DCHs. The properties of selected CR-MAC protocols have been presented and their features and parameters are shown in Table 2.1. These can help develop and design the new CR-MAC protocol to overcome the existing shortcomings in the CRAHNs. The next chapter presents the network model of the RECR-MAC protocol.

TABLE 2.1: Properties of some selected CR-MAC Protocols

Features	CREAM	DSA-MAC	BCRP-MAC	A-MAC	F2-MAC	SWITCH
Spectrum Sensing	Energy Detection	Energy Detection	Not Discussed	Not Discussed	Not Discussed	Energy Detection
Avoidance of Multi-channel Hidden Terminal	Yes	Not addressed	Yes	Yes	Yes	Yes
Best Channel Criteria	Arbitrary	Based on SINR	Based on Channel Sensed List (based on PU activity)	Channel Ranking based on Less PU activity and Bandwidth	Not discussed	Less PU and SU Activity
Physical Layer Parameters	DSSS	Not Discussed	Not- Discussed	DSSS	Not- Discussed	Not- Discussed
Spectrum Access	802.11 DCF	802.11 DCF	802.11 DCF	802.11 DCF	802.11 DCF	802.11 DCF
No of Control Frames	4	4	4	2	5	2/3
Control Channel	Dedicated	Dedicated	Assumed/ Dedicated	Assumed/ Non Dedicated	Dedicated	Assumed
Multi-Channel MAC	Yes	Yes	Yes	Yes	Yes	Yes
Use of Backup Data Channel	No	No	Yes	Yes	No	Yes
Number of Transceivers	Single	Multiple	Multiple	Multiple	Multiple	Multiple

Chapter 3

RECR-MAC Network Model

The previous chapter presents a comprehensive discussion of state of the art CR-MAC protocols, including their infrastructure, CCH, classification based single and multiple transceivers, spectrum access mechanisms, channel selection techniques and BDC strategies. The SUs can transmit information successfully without interference from the PUs and while maintaining communication links with each other, if the PUs return to its licensed channel(s) during communication. Ensuring reliable communication and maintaining links between SUs are vital in ensuring the success of CR technology. As evident from the literature review, very little work has been done to date in the area of reliable data communication based on Reliable Data Channel selection techniques with a backup data channel in Ad-Hoc CR networks.

This chapter is organised as follows: the network model and assumptions and classification of the spectrum sensing techniques for CRAHNs are discussed in Section 3.1. Section 3.2 describes the flowchart for the proposed protocol, including its phases. Section 3.3 describes the frame format of the proposed protocol. Finally, Section 3.4 covers the handshaking between the control frames over the control channel.

3.1 Network Model and Assumptions

CR technology is anticipated to offer solutions to the problems experienced on wireless networks that result from limited available spectrum bands and inefficiency, by opportunistically exploiting the existing wireless spectrum bands. In this section, a network model is presented based on CRAHNs relationship to the protocol being proposed in this study.

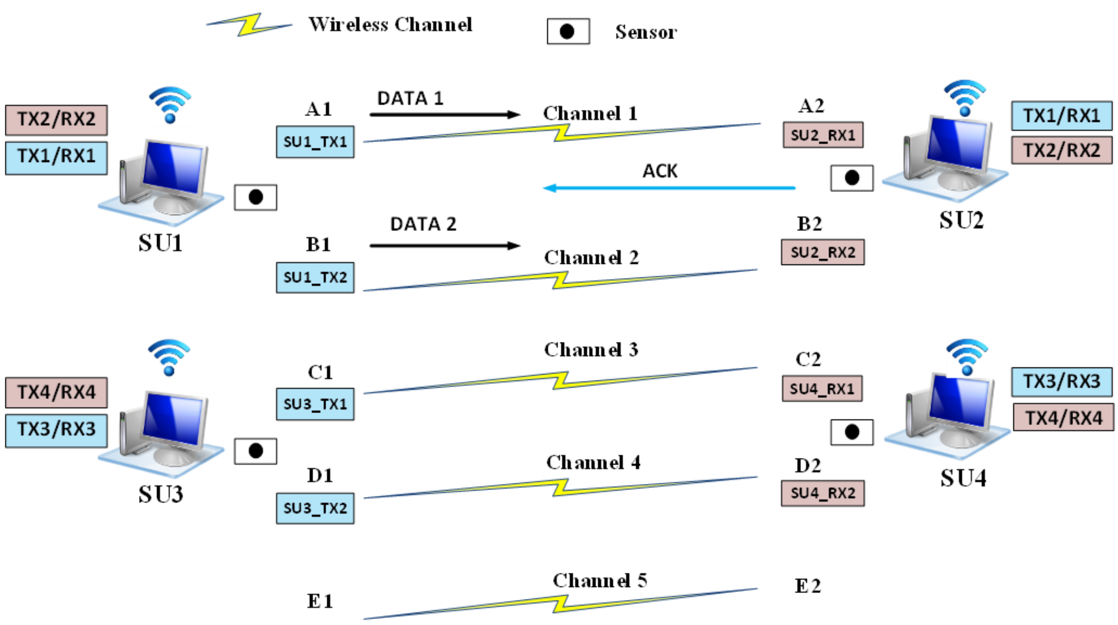

FIGURE 3.1: Network model consists of PUs, SUs, data channels, sensors, TXs and RXs

The proposed CR multi-channel network scenario, presented in Figure 3.1, is without a centralised entity, and network operations such as spectrum sensing, channel selection strategy and switching to BDC are performed by the SUs. The proposed network model is composed of two sets of users: PUs also called Incumbent Users (IUs) and SUs also called Cognitive Users (CUs) and Opportunistic Users (OUs). The PUs can access their respective licensed spectrum bands without permission and their activities have direct impact on the performance of the SUs and play a vital role in the channel selection decision. It is assumed in this study that the PUs activity can be modelled as a continuous process, known as alternating ON (i.e. the PU is in transmitting state/the "ON" state) and OFF (i.e. PU is not in transmitting state/the "OFF" state) Markov Renewal Process. The SUs record the ON/OFF activity of the PUs for the period of time in which the channel can be utilised effectively by the SUs without generating harmful interference to the PUs [94] [115] [116]. It is assumed that the SUs use the CSMA/CA mechanism to access the CCH [117]. It is further assumed that the SUs use the DCCH, which is always dedicated and may be owned by the service providers to exchange their control frames [24] [76] [23].

The SUs, however, can only access the licensed spectrum bands when the PUs are not using the channel. Moreover, in this thesis, SUs can dynamically access licensed spectrum bands, such as TVs bands and unlicensed spectrum bands, such as ISM bands (when they are in an idle state). PUs always have the highest priority to access their respective spectrum bands and should not be interrupted by the SUs [118]. Nevertheless, a number of approaches have been discussed in [83] [78] [111] [119] [120], which suggest that primary and secondary users share the same spectrum with acceptable interference. In this type of access method, called the underlay mechanism, which is usually used by Ultra Wideband (UWB) technologies, SUs are allowed to share the PUs spectrum bands in cases where the interference caused by the SUs to the PUs is below a specified threshold. In some cases of overlay mechanism, the SUs can launch their communication but when PUs become active the SUs must cancel their transmission and not transmit harmful interference toward the PUs' receivers [121].

This study proposes that each SU be equipped with two transceivers. Similar approaches have been adopted in [81] [73] [58]. These transceivers can then either transmit or receive simultaneously on two DCHs. According to Shannon's theorem, Channel Capacity (W) is proportional to Bandwidth (B), i.e.,$W = Blog_2(1 + SNR)$; thus, transmitting over multiple channels simultaneously decreases the transmission time and signal power and increases the data transmission rate [122]. In addition, each SU has an additional sensor (i.e. Receiver) with a wideband radio frequency receiver ranging from 20 MHZ to 6 GHZ coverage, which is able to detect the return of the PU and also neighbour node activity, while the receivers are occupied with DCHs. Also, the sensor is not only capable of searching, capturing and detecting a signal with high precision, but can also manage current and emerging signals [123] [124] [20] [23]. Therefore, the sensor can detect licensed channels and neighbour node activity while the transmitter and receiver are busy at DCH [125] [126]. In addition, the SUs are able to determine that the channel is unused before transmitting. Thus, the problem with collision of neighboring nodes is solved, circumventing the hidden terminal problem. The multichannel hidden terminal problem will be discussed in detail in Section 3.4 below.

To conclude, the proposed CR network model selects the reliable DCHs for the communication, thereby increasing the probability of successful communication among the SUs. In addition, this model is capable of maintaining the SUs link if the PU returns during the communication.

3.1.1 Spectrum Sensing Techniques

The spectrum sensing technique plays a vital role in CRNs, due to its sensing capabilities and awareness of its surroundings. SUs have used vacant spectrum bands adaptively by enabling spectrum sensing, regardless of out of band sensing (where SUs discover white holes over a wide range of frequency before starting the transmission) and/or in band sensing (where SUs monitor the spectrum bands during the transmission and sense the presence of the PUs to avoid interference).

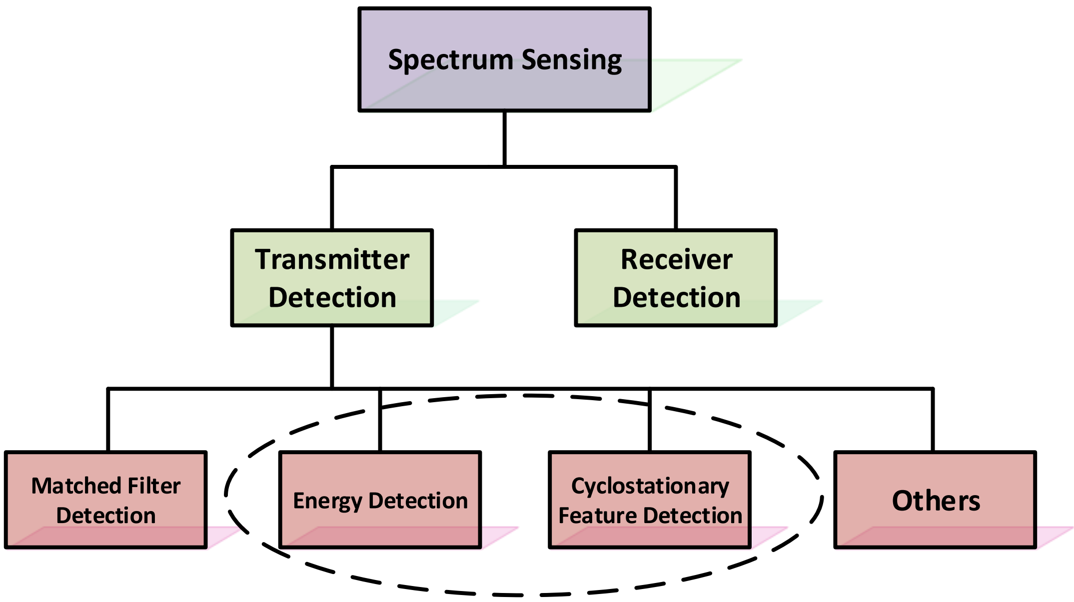

Figure 3.2: Spectrum sensing classifications (areas to which this research has contributed are shown within the dotted line)

There are several available sensing techniques able to detect the spectrum, such as matched filter detection, energy detection and cyclostationary feature detection, as shown in Figure 3.2. Covariance based detection and Wavelet based detection cannot detect the return of the PUs during SUs communication over the DCH [127] [92] [93] [128] [129].

3.1.2 Assumptions of Sensing Techniques

In this study it is assumed that during initialisation of the proposed protocol, out of band sensing is adopted, but during communication among the SUs, in band sensing is also adopted to avoid collision and interference between the primary and secondary users [66] [130] [131]. Another assumption is that the SU is working in standalone mode and makes decisions on the basis of locally gathered information. As a result, each SU has to perform independent spectrum sensing to sense the presence of the PUs [132] [133] [134] [135] [136]. It is further assumed that each SU senses the spectrum for updated information before restarting the transmission. The SU considers the white spaces and the history of the channels relative to conditions such as interference, PU returns, and positive/negative acknowledgements.

Energy detection and cyclostationary techniques are assumed in this thesis, because the hardware implementation is simple and efficient in comparison with the other detection techniques available. In addition, the energy detection technique does not require prior information about the PUs signal features, which are typically unknown by the SUs. Furthermore, it is difficult to differentiate primary and secondary users' signals. In the energy detection technique, an SU can only identify the signal of another SU but it cannot identify the PU signal. Therefore, when an SU recognises the signal, it assumes that the signal is from an SU; alternatively, if it does not recognise the signal, it concludes that it belongs to the PU. To overcome the detection of the PU during communication, the cyclostationary technique is adopted along with energy detection, which works effectively during communication over the DCH and updates the sensor about the PU returns. There is always a trade-off between accuracy and complexity when selecting the spectrum sensing technique for the CRNs. Since 2008, the FCC has permitted spectrum vendors to build a geographic database based on the available TV band spectrum bands [46]. This is an effective technique for utilising unused TV spectrum bands. Table 3.1 summarises the classification of the transmitter detection techniques.

Table 3.1: Summary of the Transmitter Detection Classification

Detection Technique	**Reliability & Accuracy**	**Delay**	**Complexity**
Energy Detection	Noise uncertainty problem cannot differentiate signals	Short sensing time in high or moderate SNR	Simplest blind
Matched Filter Detection	High accuracy if primary signal is known and synchronized	Moderate sensing time	Simple
Cyclostationary Feature Detection	High reliability	Very short detection time	Highly complex
Covariance-Based Detection	Fails when the primary signal appears like white noise	Long sensing time	Multiple antennas may be needed Very complex
Wavelet-Based Detection	Very low accuracy	Long and Fast sensing	Simple but needs to find the most suitable wavelet before the detection

3.2 RECR-MAC Protocol - Operational Framework

In this section, the complete operability of the RECR-MAC protocol is discussed with the assistance of the flowchart depicted in Figure 3.3. It is assumed that the SUs always have data to transmit. The flowchart is also presented in Figure 3.4, where it is classified into four phases:

PHASE I: In the startup stage, an SU adopts the IEEE 802.11 DCF, which is the fundamental MAC technique for accessing the channel in the Wireless Local Area Networks (WLAN). The DCF mechanism employs a CSMA/CA with a binary exponential Back Off (BO) algorithm to sense the wireless channel and gain access to the CCH. The Beacon Time (BT) includes the control and data communication time for the SUs. Figure 3.3 shows the SU must wait a short while before transmission to avoid collision, even though the channel is idle; this is known as Inter Frame Spacing (IFS). In wireless adhoc networks, IFS has two intervals with different priorities, namely the Distribution Inter-Frame Space (DIFS) and Short Inter-Frame Space (SIFS). The value of SIFS is smaller than DIFS, demonstrating its priority over other transmitting nodes. If the medium is observed as being idle for longer than the DIFS, then the cognitive nodes can transmit the frames. Alternatively, if the medium is observed as busy, the SU performs random BO by selecting a BO counter, which is not greater than the interval called the Contention Window (CW). The value of CW size has to be reset before and after every successful communication between the nodes. The BO counter decreases its value after the channel is found idle, and when the BO counter reaches zero the SUs can access the channel to exchange information.

PHASE II: In this phase, the flow of the protocol splits into two sub-phases: 1) the available SU can transmit/receive the Available Channel List (ACL) frame, which is a modified version of Ready to Send (RTS) frame, to/from the other SU within the range; or 2) if the SU receives the ACL, then the SU replies with Acknowledgement of the ACL (AACL) frame, a modified version of the Clear to Send (CTS), to the sender SU. Then a pair of SUs must exchange the control frames such as ACL and AACL in order to meet the following constraint:

$$\mu \geq 2 \tag{3.1}$$

Where μ is the number of available white spaces for simultaneous communication among the SUs. The SUs must reserve two free spaces for the data communication known as Primary Data Channel (PDC) and Backup Data Channel (BDC).

PHASE III: In this phase, if no ACL frame is found, then it is assumed that the SU will launch the ACL itself. After the SIFS time, if the SU successfully receives the AACL frame, then it must satisfy the criteria established in Equation 3.1. If the SU is unable to receive the AACL then it must wait until the expiration of the BT. Moreover, when neighbouring SUs pick up the communication between the active SUs, they then suspend their transmission for a period of time called the Network Allocation Vector (NAV). In other words, neighbouring SUs are forbidden from accessing the DCCH, until the active SUs complete their transmission and switch to the DCHs. The complete process is called Virtual Carrier Sensing (VCS), and provides updated information to the sender and receiver which is to be reserved for the next communication.

PHASE IV: It is important to note that although the reservation of the two white spaces for the SUs gives the appearance of a loss of white space, in reality it simply reduces the network convergence time by switching to the BDC if the PU returns during the communication. It also reduces the RECR-MAC protocol rescanning time, which in turn may help the SUs conserve energy, thereby reducing the computational cost. Therefore, on the basis of PHASE II and PHASE III, when the SU has satisfied Equation 3.1, it switches to a DCH for data communication.

To conclude, the novel contributions in this chapter are: when the CRAHNs is initialised, both selected DCHs are considered PDCs. If one of the DCHs become unavailable due to the PUs return, the traffic on the affected channel switches to the other DCH, which behaves as a BDC in regard to the affected traffic and continues the communication without restarting the entire process. If no PU returns during the data communication over the PDCs, then the SUs' receiver must send an ACK message to conclude communications between the SUs.

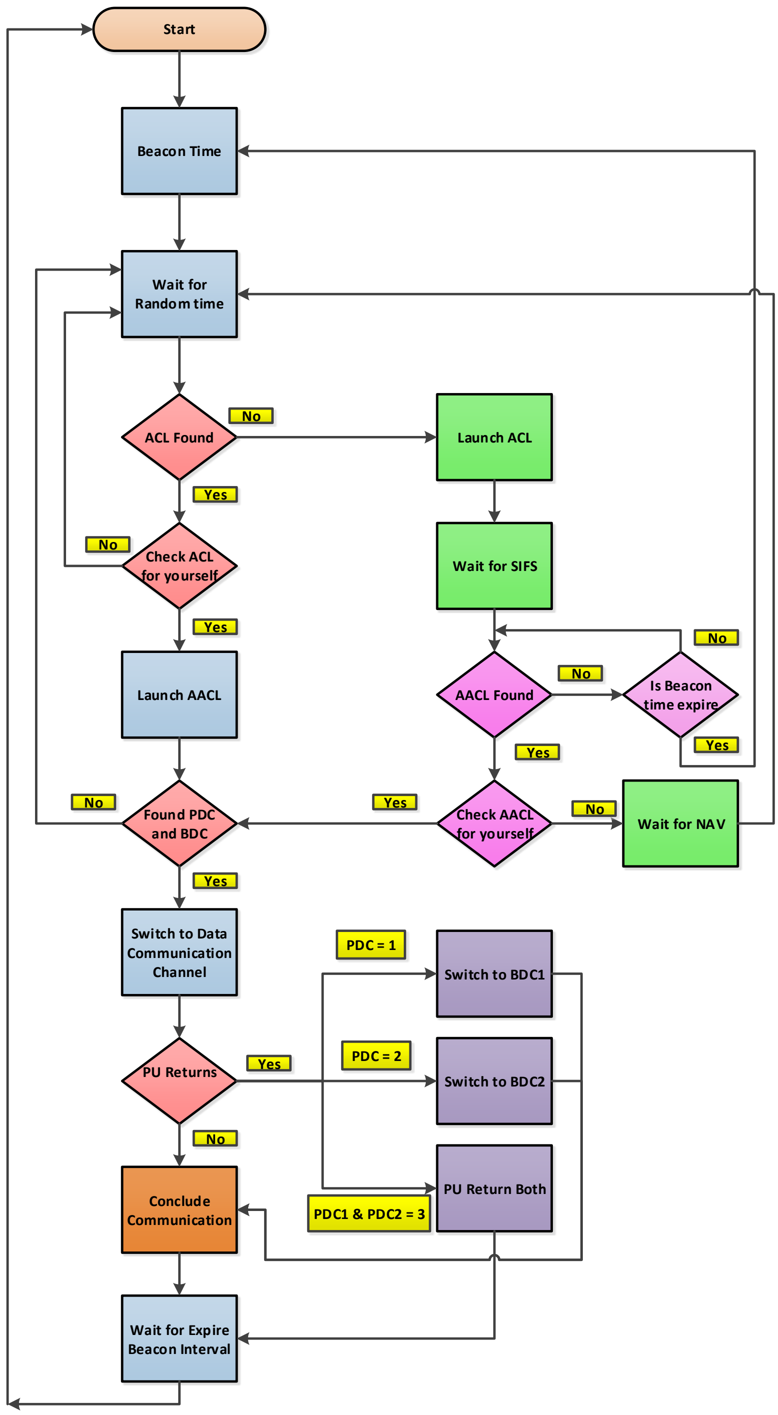

Figure 3.3: Operational Framework of the RECR-MAC Protocol

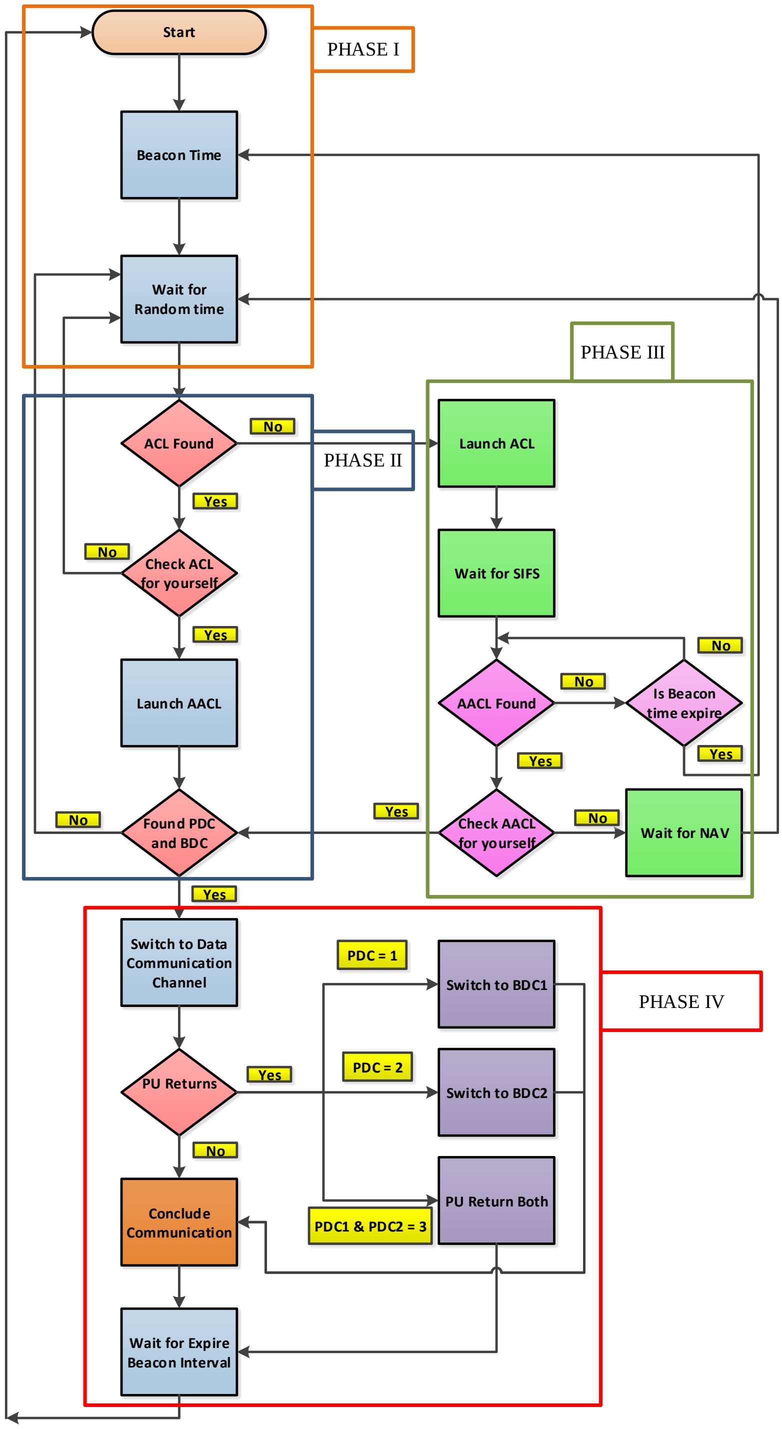

Figure 3.4: Operational Framework of the RECR-MAC Protocol with Phases

3.3 Control Frame Format of RECR-MAC Protocol

The IEEE 802.11b Distributed Co-ordination Function (DCF) uses two-way handshaking to exchange frames (RTS and CTS) for transmission over the CCH. The RTS/CTS control frames are exchanged prior to the data packet communication to reduce collision, interference and hidden node problems over the DCCH among SUs in the CRAHNs [137] [138] [139].

The ACL is introduced as a substitute for RTS and Acknowledgement of ACL (AACL) is introduced as a substitute of CTS. The structure of an ACL and AACL, which have additional fields, such as channel ranking and primary and backup data channels, is shown in Figures 3.5 and 3.6.

3.3.1 Frame Control

The frame control is comprised of 2 bytes as discussed in the following:

Protocol Version: The protocol version field consists of 2 bits as shown in Figure 3.5 with the value of 0. The new version was not yet released at the time of writing.

Type (ACL/AACL): The type is based on 4 bits, which indicates whether the frame is ACL or AACL for the SUs.

Retry Bit: The frame field is based on 1 bit; the retry bit indicates the control frames need not retransmit if the value is 0. However, a value of 1 indicates retransmission of the control frames.

Power Management Bit: The cognitive user would move to the inactive mode if the bit is this field is set as 1, otherwise the bit remains 0 and the cognitive user has to stay awake.

NAV Duration: The Network Allocation Vector (NAV) field is based on 8 bits. When two SUs are exchanging frames ACL/AACL over the CCH, neighbouring nodes pick up the communication between the active SUs and suspend their transmission for a period of time called the Network Allocation Vector. In other words, neighbouring SUs are not permitted to access the CCH until the active SUs complete their transmission and switch to DCHs.

3.3.2 Receiver Address

The Receiver Address (RA) is based on a 48 bits (6 bytes) MAC address from the receiving SU. For example, the format of the RA is: $00A0C914C829$.

3.3.3 Transmitter Address

The Transmitter Address (TA) is based on a 48 bits (6 bytes) MAC address from the transmitting SU. For example, the format of TA is: $00A0C914C828$.

3.3.4 Reliable Data Channels

This field is based on 40 bits (5 bytes), specific to the RECR-MAC protocol. This field exchanges the reliable data channel(s) list between the SUs to support data communication. Each channel requires 4 bits to represent its value. Therefore, 40 bits can accommodate a maximum of 10 DCHs during the exchange of control frames, as a limitation of the protocol that is restricted in the ACL frame in this thesis. However, the size of the reliable DCHs' field can be extended. All operations of the reliable DCHs will be discussed in Chapter 4.

3.3.5 Data Length

This field is also specific to the RECR-MAC protocol, and is based on 16 bits (2 bytes). This field describes the size of data transmitted on each DCH on the basis of multiple factors, such as the availability of free time, history and conditions of the DCHs to avoid retransmission among the SUs. All operations in this field will be discussed in the following chapters. Following is the ACL frame format with additional features of reliable data channels and date length.

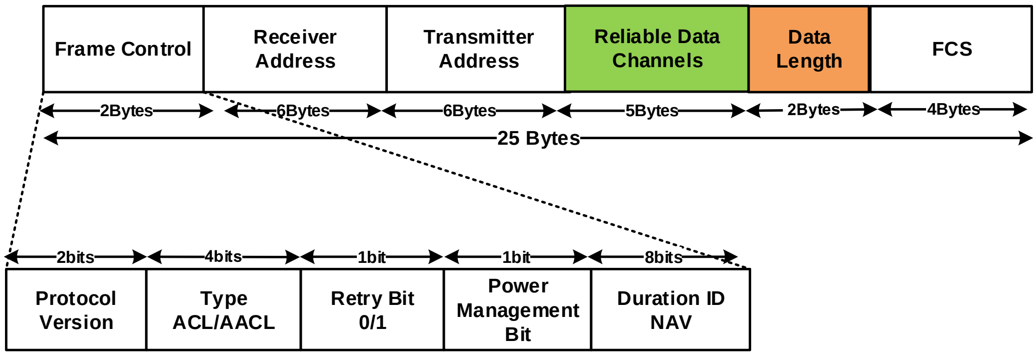

FIGURE 3.5: ACL frame format

3.3.6 Frame Check Sequence

This Frame Check Sequence (FCS) field is based on 32 bits (4 bytes). This provides a Cyclic Redundancy Check (CRC) at the end of the frame to check its integrity; this occurs whether or not it is a valid frame.

3.3.7 Reliable Channel Identification

The Reliable Channel ID field is specified for the RECR-MAC protocol based on 8 bits (1 byte), as part of the AACL frame, where each 4 bits describe the reliable channel ID. This field provides the list of two reliable channels for data communication.

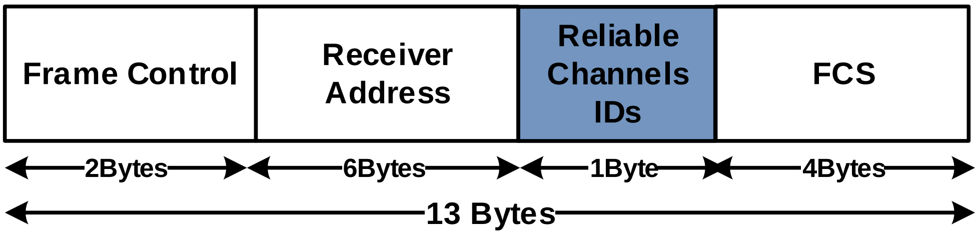

FIGURE 3.6: AACL frame format

3.3.8 Acknowledgement (ACK) Frame

The Acknowledgement (ACK) frame in Figure 3.7 is generated after the successful completion of data communication between SUs. When an ACK is received from the receiver of the receiving SUs, the SUs update their information and channel ranking, which then has a direct impact on the quality of the DCHs. The successful or unsuccessful ACK frame has an impact on the selection criteria of the DCH for the next possible communication. In case of a successful ACK, the SUs increase the probability of the channel condition. In case of an unsuccessful ACK, the SUs decrease the channel condition and may decrease the channel ranking (this will be discussed in further detail in the following chapters).

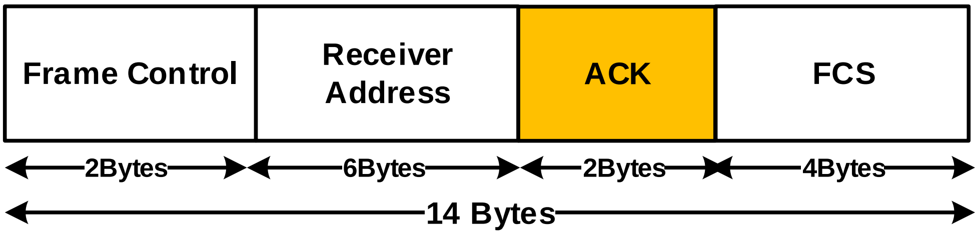

FIGURE 3.7: ACK frame format

In this chapter, the AACL and ACK frames used to confirm receipt of the frames from the sender cognitive user. The sending cognitive user have the TA/RA of the receiving cognitive user. Similarly, the receiving cognitive user have the TA/RA of the sending cognitive user. During the initialisation of the network, the sending node must exchange its TA address and RA of the receiving cognitive node to confirm the participating cognitive users. However, once the receiving cognitive user successfully receives the ACL frame from the sending cognitive user, then; it replies with AACL with only the RA address of the sending cognitive user to make sure that the confirmation goes to the participating sending cognitive node instead of any other non-participating cognitive users which may introduce the additional delay in the network. Moreover, the sending cognitive user is only expecting the confirmation frame such as AACL and ACK from its participating cognitive nodes only. If the AACL and ACK frames do not receive within the described time duration then the sending cognitive user re-transmits the entire frame. Thus, the reduction in size of the AACL and ACK frames has an impact on the communication time and energy consumption in the CRAHNs. This approach has been validated by other researchers in this area [34] [35] [20].

3.4 Exchange Operation of the Control Frames

With the IEEE 802.11b DCF mechanism, the SUs preserve the channel(s) to exchange control information, ACL and AACL frames, over the DCCH. The proposed RECR-MAC protocol is applicable for the IEEE 802.11 a/b/g/n standards. However, the parameters of the IEEE 802.11b used in this study validates the comparison of the proposed RECR-MAC protocol and other CR-MAC protocols considered in the following chapters. In Figure 3.8 each SU waits for a short while prior to transmission, in order to avoid the collision, although the channel is idle; this is called Inter-Frame Spacing (IFS). In wireless adhoc networks, IFS has two intervals with different priorities, the DIFS and SIFS.

For example, in Figure 3.8, SU A has to wait for a duration equal to the DIFS time before transmitting the ACL. Similarly, the receiving SU B has to wait for a a duration equal to the SIFS time before transmitting AACL. The value of SIFS time should be smaller than the DIFS time in order to demonstrate its priority over other transmitting nodes. Neighbouring nodes overhear communications between SUs A and B and therefore suspend their transmission for the period of time defined in the duration field of the ACL/AACL, called NAV. This entire process is called VCS, and continually provides up to date information to participating SUs to avoid collisions and reserve the channel for the exchange of control information. If the medium is observed as idle longer than DIFS, then, the other SUs can exchange their ACL/AACL frames. Alternatively, if the medium is observed to be busy then it can perform the random BO by selecting a BO counter, which is not greater than the interval of CW. The value of the CW size has to be reset before and after every successful communication between the SUs. SU transmission occurs when the BO counter reaches zero as it decreases each slot after the channel is observed as being idle. The ACL/AACL frames reserve the CCH and also avoid collision between the neighbouring SUs, thus finally solving the hidden terminal problem.

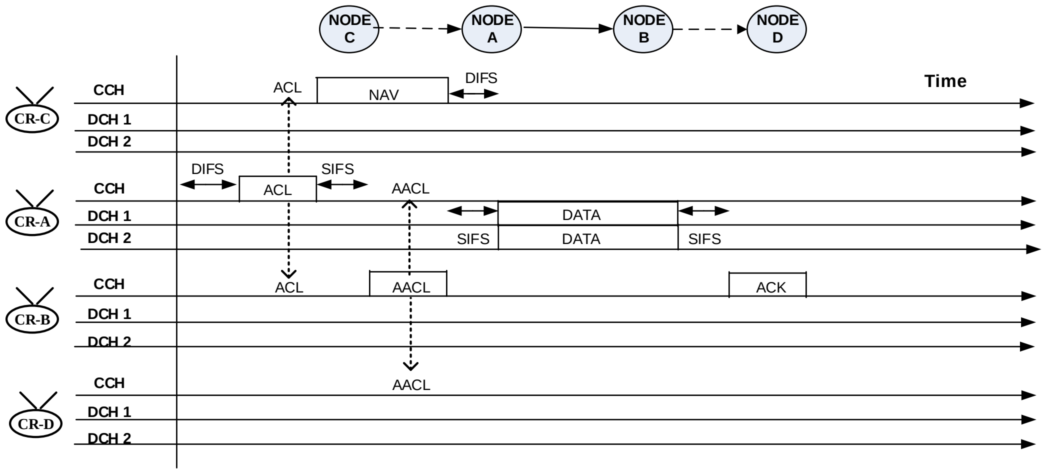

Figure 3.8: Exchange of ACL and AACL frames

The scanning / sensing process of the DCCH by SUs before launching the ACL/AACL is demonstrated in Figure 3.9. The waiting time to launch the ACL is proposed to be equal to the DIFS time to avoid duplication and collision among the CR nodes. If there is no ACL found, then it is assumed that SU A launches the ACL containing additional information such as the reliable channel(s) list and data length as compared to the standard RTS control frame first. Assuming that SU B wins the contention among the rest of the SUs and has common channels (1 and 2) with the same ranking as node A, then AACL is sent in reply by SU B with additional information such as the channel ID of primary and backup data channel(s). Conversely, SUs C and D set their NAV, and do not attempt to access the DCCH until the NAV expires, as shown in Figure 3.8 to avoid the hidden terminal problem [138]. After a successful exchange of ACL/AACL, the SU sender A begins transmitting the frames to the SU receiver B over the PDCs. If no PU returns on both selected DCHs during the communication, then SU receiver sends ACK to the SU sender after receiving the frames from the SU sender successfully. If the PU returns over DCH 1, then the DCH 2 is said to act as a BDC and vice versa. In the worst case, if the PU returns over DCHs 1 and 2 simultaneously, then the SUs must restart the entire procedure. As discussed above, the PUs can return any time, due to their legal right to use the channel without any pre-notification. However, based on the proposed reliable channel selection criteria, there would be less chance that the PU returns on both occupied DCHs simultaneously. A sensor at each cognitive node will be able to detect the return of the PU while the transceivers are busy with other DCHs. After every transmission (successful or failed), each SU records the unused channels and updates its channel list, before initiating the new connection with other cognitive users, to avoid the multi-channel hidden terminal problem [76]. Also, the sensor is not only capable of searching, capturing and detecting a signal with high precision, but can also manage current and emerging signals as discussed in [123] [124] [20] [23]. The sensor can detect licensed channels and neighbour node activity while the transmitter and receiver are busy at DCH [125] [126]. Thus, the problem with collision of neighboring nodes is solved, circumventing the hidden terminal problem and multi-channel hidden terminal problem.

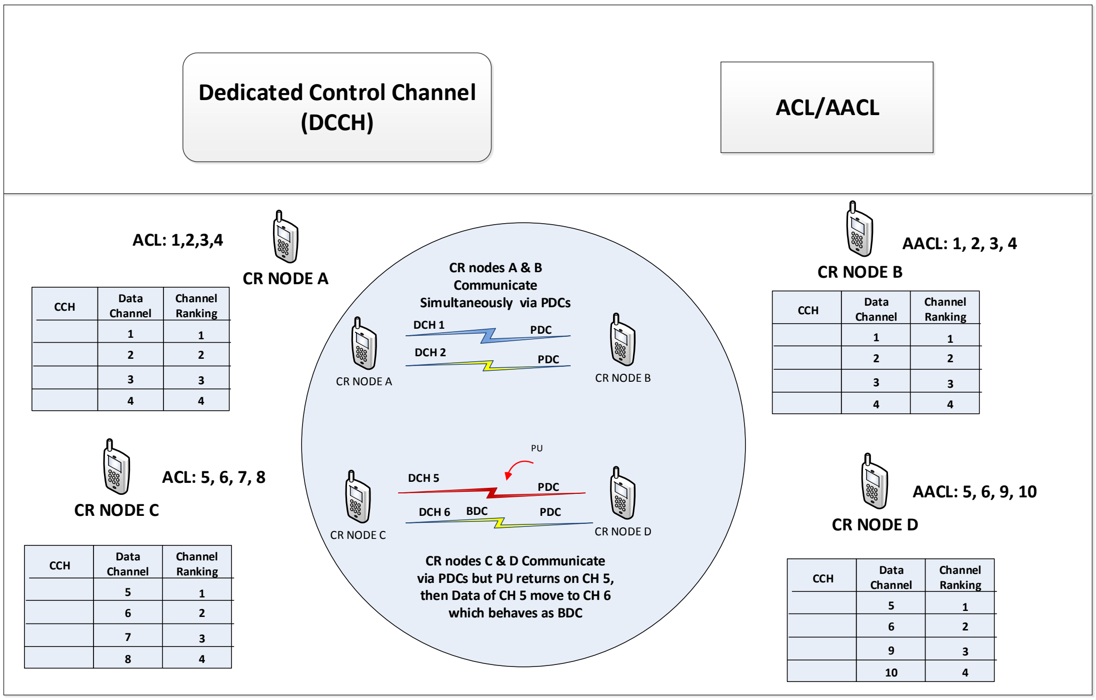

FIGURE 3.9: Communication over primary and backup data channel(s)

3.5 Summary and Contributions

This chapter presented the model of the proposed RECR-MAC protocol along with the aim and objectives of this study. The flowchart of the proposed protocol consists of four phases. Each phase was discussed in terms of the operation of the SUs. The framework of the four phases was discussed in the context of both PU return and no PU return, with a detailed description given of how the situation would be managed without restarting the entire process if the PU returned during the data communication. A description of the frame format and frame handshaking functionality of the SUs over the CCH is given at the end of the chapter. The next chapter presents the channel selection process and its impact over communication time for RECR-MAC protocol.

Chapter 4

Channel Selection Process and its Impact over Communication time for the RECR-MAC Protocol

Cognitive Radio (CR) has proved to be the smartest emerging technology in the wireless family to efficiently reuse spectrum bands and resolve issues of spectrum scarcity. However, issues still remain concerning reliable and successful communication among the SUs, particularly when it comes to maintaining the SUs' link when PUs return during communication. The importance of channel selection techniques for data communication between SUs has been comprehensively discussed in previous chapters. Related work has demonstrated that one of the primary aims of CRNs is to utilise the unused spectrum efficiently by switching control and data information between the SUs, as shown in 4.1.

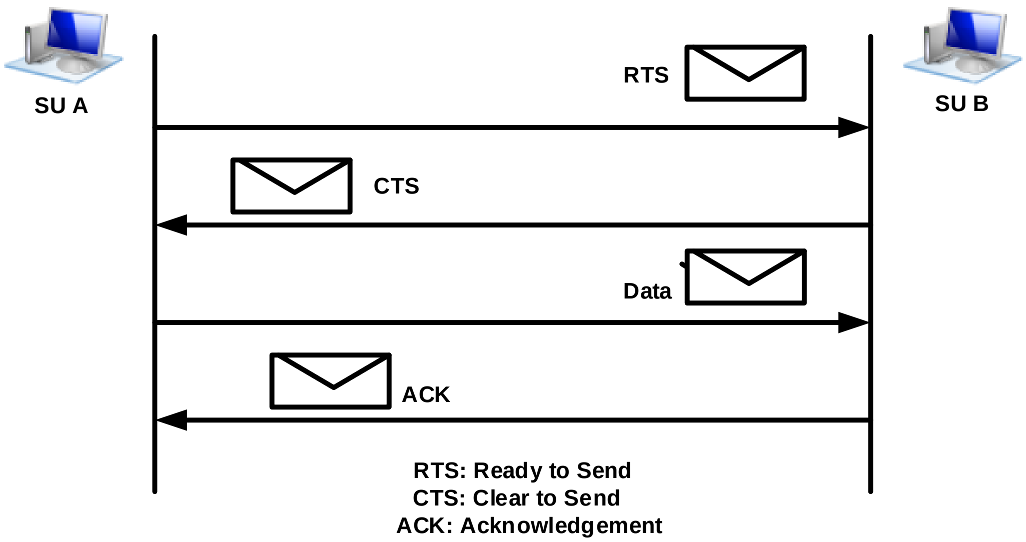

Figure 4.1: Exchange of control and data information between SUs

Since the inception of the CR technology, researchers have advanced in the area of spectrum sensing by using well known spectrum sensing methods, fusion centre and geo-location databases [140] [141] related to the physical layer. The fusion centre and geo-location databases hold the updated information of each SU (such as SNR, ON and OFF activity of the PUs) along with other channel conditions for the selection of reliable channels. Based on the spectrum sensing, fusion centre and geo-location databases, SUs can select the DCHs to exchange information among themselves. As discussed in the literature review, the majority of authors have an adopted random DCH strategy without any consideration of criteria, which may lead to an inability to continue the communication among the SUs if interference occurs during communication. A small number of authors have selected DCHs based on SNR, load balancing, shortest route and data rate. The channel selection criteria under discussion may lead to the selection of DCH channels with low quality and/or frequent arrival of PU activity, which then decreases the probability of successful communication among SUs and requires an increased length of time to complete the communication process. However, the proposed RECR-MAC channel selection technique in this study has not yet been adopted to select reliable channel(s) for data communication. The criteria for reliable channel selection for the RECR-MAC protocol are based on channel ranking, minimum activity of the PUs, number of ACKs and the history of the communicating channel(s).

A further major challenge is to maintain the SUs' links when PU returns over the DCH. Some researchers have proposed the backup control and data channels in the literature review, but this approach is only feasible if more than one DCH is found during channel sensing. However, the proposed RECR-MAC protocol select a minimum of two DCHs to transmit the data over both DCHs simultaneously, which form backups for each other if the PU returns to any selected DCH. The RECR-MAC protocol selects channel selection criteria and BDC simultaneously, which increases the reliability of the SUs' communication, reduces communication time, energy consumption and delay, thus reducing the number of overheads over the CCH and re-transmissions among the SUs, and increasing the network throughput.

The remainder of this chapter is organised as follows: Section 4.1 gives a detailed description of the classification of the channel selection criteria. Section 4.2 gives a detailed comparison of the handshaking operation for the selected benchmark CR-MAC protocols. Section 4.3 discusses the framework of the channel selection process for the proposed RECR-MAC protocol and its impact over the CRAHNs. Section 4.4 discusses the importance of communication time in relation to the control and data channels. Section 4.5 provides a comparison between the proposed RECR-MAC protocol and other CR-MAC protocols by using timing diagrams with, and without, BDC. Section 4.6 explores details of the comparison of communication time between RECR-MAC and benchmark CR-MAC protocols with, and without, backup data channels.

4.1 Channel Selection Criteria

As discussed in the literature review, it is difficult to establish the coordination among SUs, particularly in the infrastructure-less CRNs, with no centralised entity available to manage and select the channels, and it is also difficult to achieve robust communication over the DCH. In reality, the reliable selection of DCH has a strong impact on robust data communication among the SUs. Therefore, instead of random DCH selection, it is important to adopt certain criteria for DCH selection to increase the probability of successful data communication among the SUs. In CRNs, SUs share the PU spectrum bands without interference occurring between them. The SU must be able to determine the available spectrum bands, in order to: i) select the available channel/portion of the spectrum; ii) to access the spectrum bands and use the available channels; iii) to vacate the DCH immediately if PU returns.

CR technology requires two types of channels such as control and data channels to exchange information among SUs. DCCH facilitates SUs to exchange their control frames, select the DCHs for exchanging data and then ACK frames to conclude the successful communication. The CR-MAC protocols are classified into the following four main groups, based on channel selection process and the BDC, as shown in Figure 4.2.

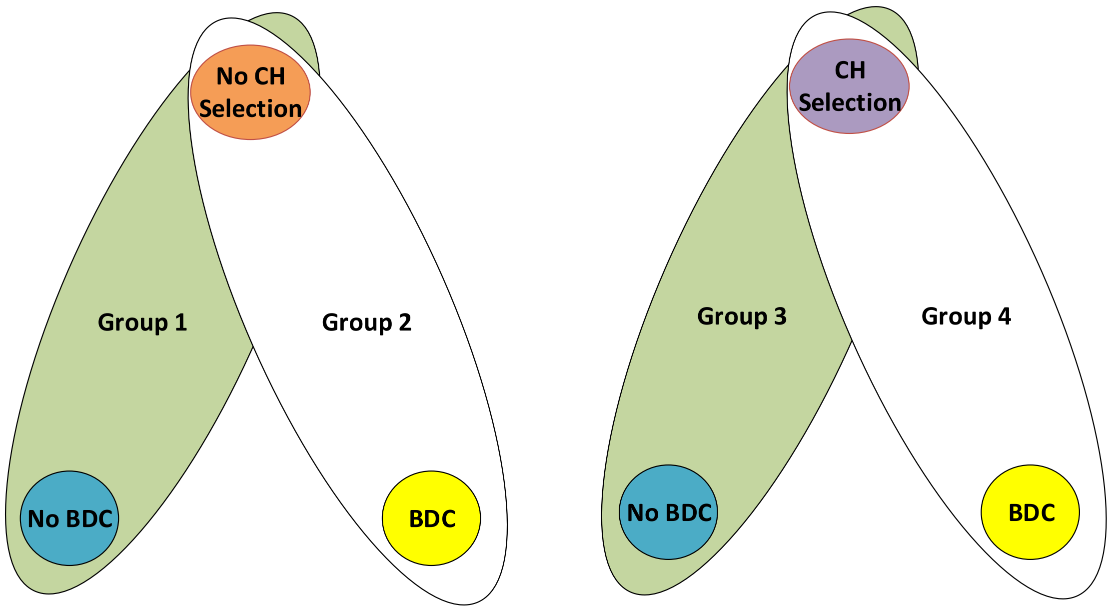

Figure 4.2: Groups of channel selection criteria

Group 1 (No CH Selection Criteria and No BDC): A random DCH without consideration of any criteria and BDC have selected in [81] [24] [62] [76] [78] [85] [25] [23]. Due to the absence of the DCH selection criteria and a BDC, the SUs may select the wrong channels and thus unable to continue the communication if PU returns. The CRNs may decrease the probability of successful communication, due to the selection of DCHs with high interference and/or frequent arrivals of the PUs, which may increase communication time and energy and thus reduce network throughput.

Group 2 (No CH Selection Criteria and BDC): In [18] [57] [113] [21] [114], BDC has introduced to avoid the re-negotiation over the CCH and reduce the control overheads. The authors select a random DCH without any criteria that decreases the probability of successful communication due to an incorrect selection of the DCH. However, the BDC is introduced in order to maintain the SUs' link if PU returns during the data communication. Without considering any channel selection criteria, the SUs may select DCHs with high interference as primary and backup data channels. This can lead to longer communication times and greater energy requirements and low network throughput.

Group 3 (CH Selection Criteria and No BDC): In [142] [102] [103] [104] [19] [90] [20] [77] [76] [105] [89] [88] [106] [107] [111] [91] [108], multiple goals have achieved by using channel selection techniques based on the following techniques: operating range; channel capacity; low PU occupancy; length of free time; last unused scanned channel; data rate and load balancing. These techniques may increase the reliability of the DCHs and the probability of successful communication between the SUs. SUs are only able to utilise the spectrum bands when PUs are not using their own spectrum bands. The SUs of Group 3 are unable to maintain the communication link if PU returns to the DCH as the owner of the channel. Therefore, the SUs must re-start the entire process, so introducing overheads and an increase in communication time and energy consumption in the CRN. Moreover, the frequent arrival of the PU degrades the quality of the DCH and reduces the opportunity for subsequent iteration of the communication among the SUs.

Group 4 (CH Selection Criteria and BDC): Channel selection criteria and BDC have considered in this group. The channel selection criteria assists in selecting the most reliable DCHs for data communication based on the least PU activity and a higher bandwidth. In addition, if PU returns during the ongoing communication, the SU switches to BDC instead of re-starting the entire procedure. This saves communication time and energy and increases network throughput.

In [58], unlicensed spectrum bands for the BDCs have selected. However, if there is no unused channel available from the unlicensed spectrum, the channel from the licensed spectrum with the least PU activity is considered as a BDC. If more than one channel has the same priority, then the BDC is selected randomly. This is neither an effective nor reliable approach. In addition, this proposed technique may select a DCH with high interference, due to frequent arrivals of the PUs, which reduces the quality of the channel. The selection of the unlicensed spectrum bands for the BDC is not an efficient approach, due to the fact that these spectrum bands are generally more crowded compared to the licensed spectrum bands. It is therefore difficult to maintain the unlicensed spectrum bands for length of time and use them as a BDC. In the researcher's opinion [58], the BDC is considered from the licensed spectrum bands (such as TV bands), instead of unlicensed spectrum bands, in order to increase the reliability of the ongoing data communications.

The BDC is considered if more than one channel is available from the channel sensing [73]. This protocol is capable of sensing n numbers of DCHs, which is not possible in practice. However, a channel with highest bandwidth is ranked as DCH 1 and a DCH that has least bandwidth is ranked as the lowest ranked channel in the cognitive network. Thus, this approach is not applicable if a single DCH is available during the exchange of control information. In such a case, there is no BDC available to continue the communication if PU returns.

4.2 Handshaking Operation of the benchmark CR-MAC protocols

In this section, there is a detailed discussion of the handshaking operation of the benchmark CR-MAC protocols (CREAM-MAC, DSA-MAC, RMC-MAC and SWITCH-MAC). The selection of control and data channels for the benchmark CR-MAC protocols are discussed in the following sub-sections.

4.2.1 CREAM-MAC Protocol Handshaking Operation

The CREAM-MAC protocol exchanges six types of frames for handshaking over the CCH and DCH among the SUs. The CCH frames are called RTS/CTS and Channel State Transmitter (CST)/Channel State Receiver (CSR), and the DCH frames are called Data and ACK. The key function of RTS/CTS frames is to solve the hidden terminal problem and prevent the neighbouring SUs from not selecting the occupied channel. The function of CST/CSR frames is to coordinate the information of the unused channels between the sender and receiver of the SU for data communication. The CST frame maintains information concerning unused channels for the transmitting SU, whereas the CSR frame holds the information about unused channels for the receiving SU. In the CREAM-MAC protocol, SUs are required to give an additional two handshakes over the CCH to select the DCH. Thus the key function of the RTS/CTS is to avoid the interference and collision among the SUs, while the CST/CSR avoids collisions between the SUs and the PUs.

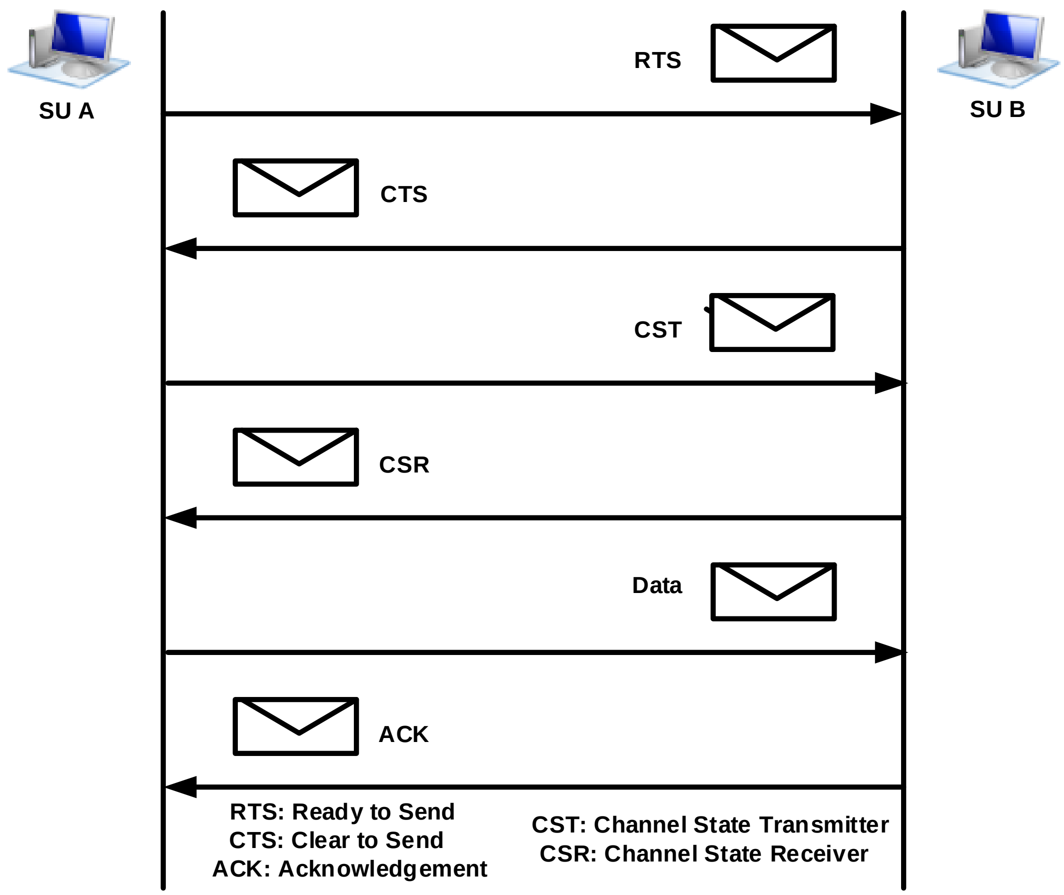

FIGURE 4.3: Handshaking operation of the CREAM-MAC protocol

If more than two DCHs are available, then CREAM-MAC utilises all available DCHs in order to increase the throughput and reduce the communication time. This increases the cost of the hardware (such as n transceivers and n sensors). In addition, the CREAM-MAC protocol fails to address the selection criteria of the DCHs, particularly if more than one DCH is available after an exchange of control frames. The SUs may be required to transmit an equal amount of data over each available channel, and/or transmit increased data over the channel with the highest bandwidth and/or transmit the data on the channel with the least PU activity. Moreover, the CREAM-MAC protocol is unable to address the issue of how to continue the communication if PU returns during the data communication. Due to the absence of BDC, the CREAM-MAC protocol restarts its entire operation, which may cause additional delay and increase overall communication time and energy, along with reducing network throughput.

4.2.2 DSA-MAC Protocol Handshaking Operation

The DSA-MAC protocol adopts four-way handshaking for exchanging control information and two-way handshaking for exchanging data information among the SUs such as CREAM-MAC. The control frames are named Frequency Request/Frequency Reply (FRQ/FRP) and two ACK Hello frames. The DSA-MAC protocol is introduced in the Spectrum Status Table (SST) that records the values of channel ID with the occupied and unoccupied status of the channel(s) and the SINR based on the spectrum sensing technique. In addition, there are two types of hello messages: one that is exchanged periodically (enhancing the spectrum sharing), while the other is exchanged after the completion of the data communication, updating the SST table and the status of the neighbouring SUs. FRQ/FRP is exchanged over the DCCH allocate available DCHs for the data communication. Moreover, the data transmission and ACK frame are exchanged in the designated DCHs. The selection criteria of the DCHs are based on the highest SINR values.

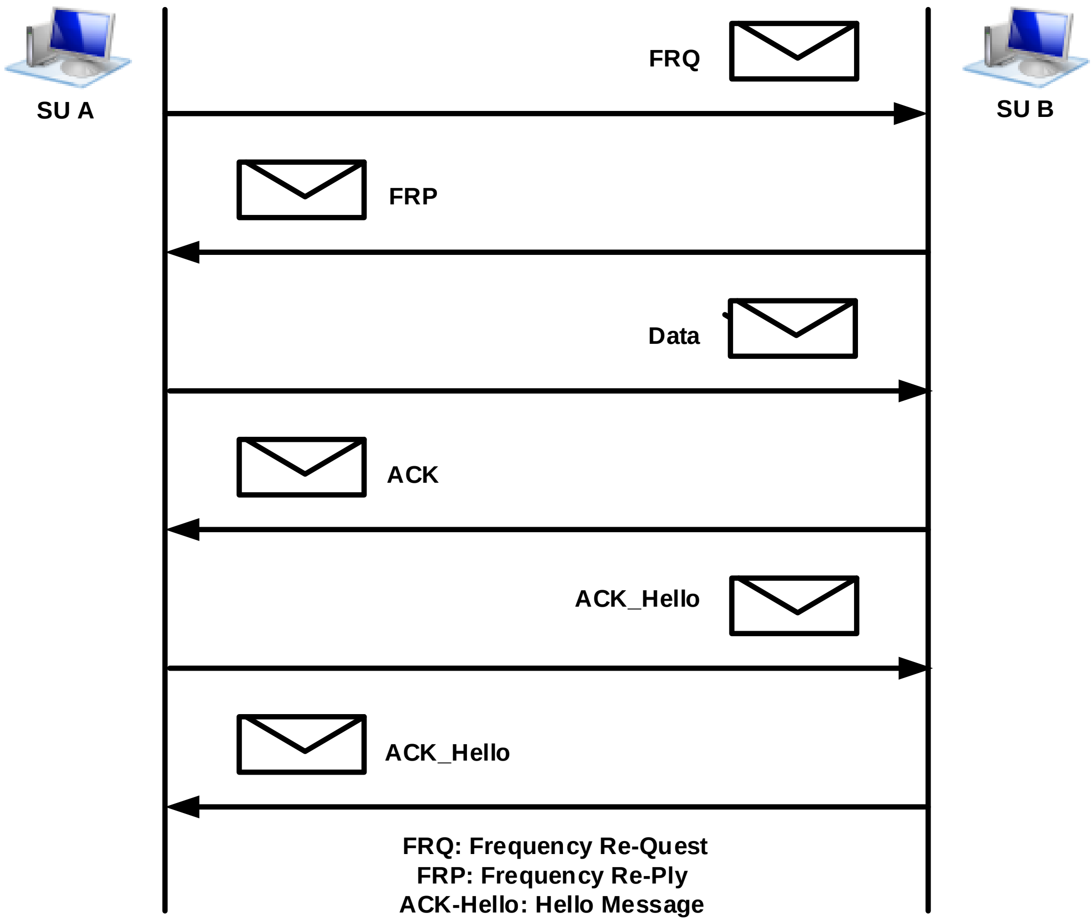

FIGURE 4.4: Handshaking operation of the DSA-MAC protocol

The main objective of the additional hello frames is therefore to enhance spectrum sharing among the SUs. In addition, the DSA-MAC protocol increases network throughput and Quality of Service (QoS), by allowing SUs to access multiple DCHs simultaneously, if more than one DCH is available. However, the DSA-MAC protocol fails to address the situation if channel 1 has low SINR in comparison with channels 2 and 3, but has high unused/free time for data communication as compared to channels 2 and 3. In this case, the DSA-MAC protocol selects Channels 2 and 3 on the basis of high SINR that may reduce the opportunity to successfully complete the data communication, which in turn reduces the QoS and overall throughput of the network.

4.2.3 SWITCH-MAC Protocol Handshaking Operation

The SWITCH-MAC protocol has two modes of handshaking over the CCH and DCH: i) an exchange of the RTS/CTS if there is no PU return during the communication; ii) an additional frame named Notification To Reserve (NTR) is sent by the receiver to its neighbour if the RTS/CTS each have a different list of the available channels for communication. The NTR has the same frame format as the CTS. There are two types of DCH being adopted in SWITCH protocol, including the Licensed Channel (LC) and the Unlicensed Channel (UC). The LCs are utilised in data communication with no PU returns. However if there are PU returns, then UCs are considered as a BDC. If there is no BDC available from the UC, then the LC channel with the least PU activity is considered as a BDC. Priority is assigned to each channel based on their available free time. In addition, the channel with least PU activity and Classical User (CU) activity is given the highest priority for the data communication. The priority of the channels is based on High=H, Medium=M and Low=L. If more than two channels have the same priority, then the DCH needs to be selected randomly.

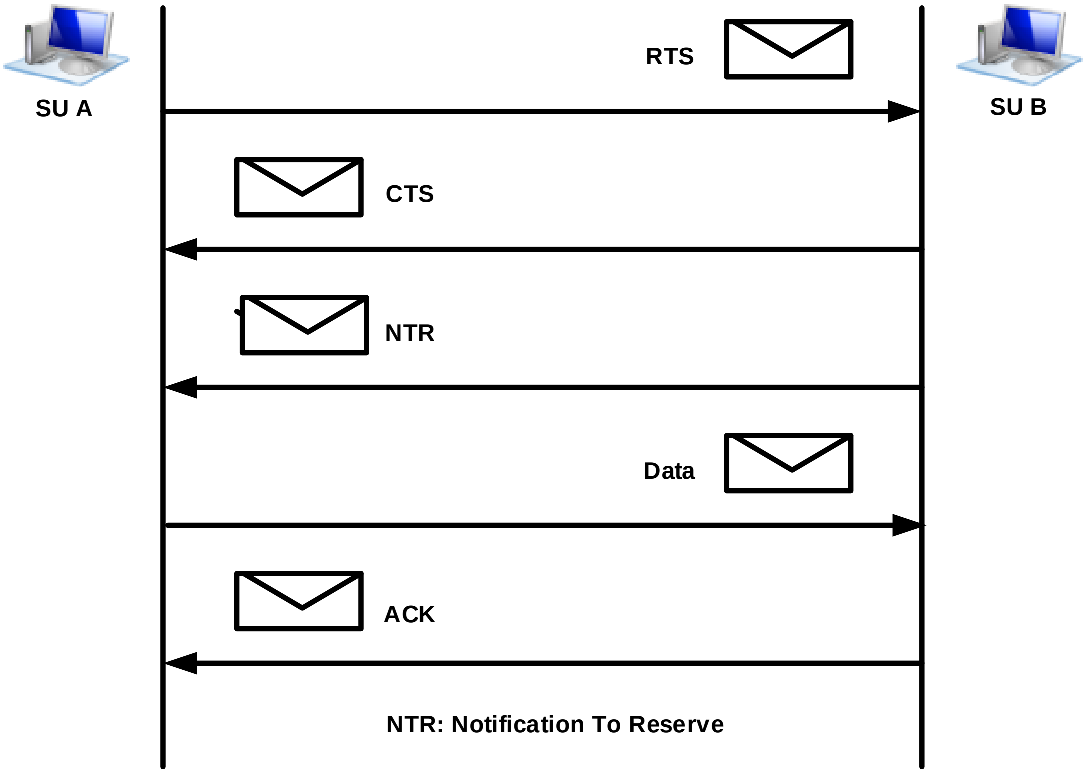

FIGURE 4.5: Handshaking operation of the SWITCH-MAC protocol

The SWITCH protocol is unable to address a number of the challenges during the design of this protocol. For example, the Free Channel List (FCL) updates its available channel list (including the PDC and BDC) to its neighbours. If the PU returns over the selected DCH, then the SU switches to the BDC as assigned in the FCL. However, if the SUs find that the BDC is already occupied by the PU, the SWITCH protocol needs to re-establish its complete process, which reduces the throughput and QoS and increases both communication time and the energy of the network. In addition, the SWITCH protocol selects the DCH from the LC, but in a situation where all the selected LCs have free time that is lesser than that of the free time of the UCs. The SWITCH protocol always selects the LC based on its design, which may decrease the network throughput. Even if more than one channel is available with the same priority for data communication, the SWITCH protocol always selects random DCH. For example, if a random DCH is selected with high PU returns (as compared to the other available DCHs with low PU activity), this reduces the network throughput and increases communication time and energy, particularly when the traffic load of the PU increases.

4.2.4 RMC-MAC Protocol Handshaking Operation

The RMC-MAC protocol requires two-way handshaking over the CCH named as RTS/CTS two-way handshaking when exchanging data information among the SUs during normal operation. The RMC protocol introduces a Reserved Sensing Period (RSP) if PU returns during the data communication, which requires a four-way handshaking. During the RSP, the SUs is constantly recording the interference level of the used channels. If PU returns to its LCs based on the threshold of the interference level, SUs broadcast an Emergency Beacon (EB) which alerts the presence of the PUs to the active SUs. Subsequently the active SUs leave the channel immediately, without any harmful interference to the PUs. The EB also provides a list of available channels to the SUs, in order to maintain the link and avoid the need to re-establish the entire process. SUs select the best DCHs based on the EB and forwards the request to the neighbouring SUs by using a Handoff Beacon (HB) over the CCH. Alternatively, data communication is terminated and SUs are forced to contend for the newly available unused channels.

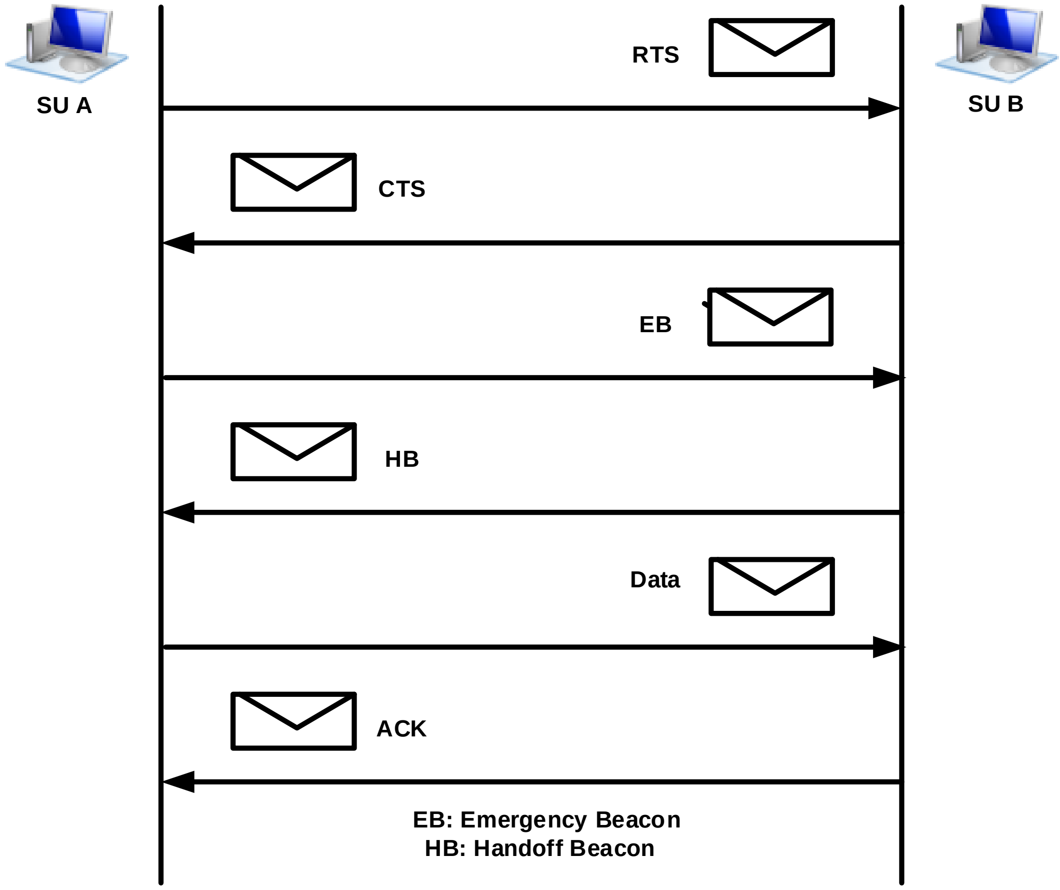

FIGURE 4.6: Handshaking operation of the RMC-MAC protocol

Without considering any channel selection criteria, the RMC protocol may select a DCH which has a high PU activity and/or does not have a good quality channel. In addition, the RMC-MAC protocol cannot address the selection criteria of the BDC if the PU returns over the PDC during the communication. It may be possible that the selected BDC does not have sufficient free time to transmit the entire data set, which may decrease network throughput and increase communication time and energy.

4.3 Channel Selection Process for the RECR-MAC Protocol

The RECR-MAC protocol selection process for the DCH is specifically designed for the CRAHNs, as shown in Figures 4.8 and 4.9. The key goal of designing the RECR-MAC protocol is to increase reliability in terms of successful communication amongst the SUs. In [142] [102] [103] [58] [73], the single case of channel selection process is discussed but it is hard to understand the entire process. Therefore, the RECR-MAC protocol divides the entire channel selection process into three cases for comprehensive understanding of each step. In addition, the RECR-MAC protocol introduces reliable channel selection process, rather than random selection criteria.

As discussed in the section above, the CREAM-MAC and RMC-MAC protocols have selected random DCHs that may include channels with a high PU interference and/or less available free time. However, the main difference between these two protocols is that when PU returns over the DCHs, the CREAM-MAC protocol is required to restart the entire process, while the RMC-MAC protocol switches to the available BDC and continues its communication. Due to the random selection of the DCH, frequent PU returns could happens during the transmission process, which increases the communication time among the SU.

The DSA-MAC and SWITCH-MAC protocols have selected DCH based on SINR values and PU occupancy, respectively. However, if PU returns during the communication of the DSA-MAC protocol, then it has to restart the entire process, while the SWITCH-MAC protocol is able to continue the communication due to the availability of the BDC. The selection criteria of the SWITCH-MAC protocol has not addressed the situation if two or more DCHs have the same priority. Initially, the SUs have scanned the activity of the PUs. They have sensed the unused spectrum bands and recorded the timing activity of each DCH. If SUs are unable to find any free time for their data communication, then it may restart the scanning process.

In order to overcome these existing challenges, the RECR-MAC protocol is proposed as a framework with channel selection process, which provides a solution to re-establishing the connection of the SUs without additional handshaking over the DCCH, in a situation when the PU returns over the DCHs during the communication. To get a clear understanding, the reliable channel selection process is divided into three (3) cases as shown in Figures 4.8 and 4.9. Case I selects the reliable DCHs based on channel ranking, Case II selects the reliable DCHs with channel ranking and history of the channels, and Case III provides the solution to continue the communication if PU returns.

The following three cases describe the channel selection process such as initialisation of the cognitive network, activity of the SUs after initialisation of the network, and manage the SUs activity if PU returns during the communication, in more detail:

Case I : Based on the Case I reliable DCH selection criteria, initially all SUs record the activity of PUs over each DCH, as shown in Figure 4.7. This figure reveals the activity of the PUs over the DCHs. The x-axis shows the PUs' activity over the DCH and the y-axis shows the amplitude of the data size in the format of ASCII characters. The maximum available time is 2100 μs for the PUs and SUs to exchange their information. In this scenario, the DCHs with less PU utilisation are considered to be the most reliable DCH, when compared to other DCHs. The sequences of all DCHs are then organised and ranked, based on the maximum free time.

FIGURE 4.7: PUs activity over the DCHs

For example, Table 4.1 shows that DCHs 10 and 9 have maximum free time based on the least PU occurrences (PU_{OC}^{LEAST}) on these DCHs. Therefore, these two DCHs are selected as the most reliable channels for the first pair of the SU. The following priority of the DCHs are 8 and 7, respectively, for the other pairs of SUs.

TABLE 4.1: Free available time and ranking over each DCH (μs)

CH1	**CH2**	**CH3**	**CH4**	**CH5**	**CH6**	**CH7**	**CH8**	**CH9**	**CH10**
966	984	1004	1023	1043	1062	1088	1107	1127	1146

Case II: Based on the reliable DCHs selection criteria of Case II, the CR network has been initialised with some history over the DCHs. The Reliable DCH (R_{DCH}) selection criteria is then further enhanced, based on additional parameters, such as channel ranking (CH_{RANK}) and the number of times the channel is being utilised (NT_{CH}^{USAGE}) for the SU's communication. The value of the CH_{RANK} is increased on the basis of the number of positive ACKs ($ACK_{NUMBER}^{Positive}$) received from the SU's receiver and vice versa. If more than two DCHs have equal values (as in the case of the SWITCH-MAC protocol), then the RECR-MAC protocol is required to modify its approach and select the two most reliable channels with the least PU activity, as compared the other DCHs. Thus, the CH_{RANK} is directly proportional to the $ACK_{NUMBER}^{Positive}$ (and vice versa) but also considers the past history of the DCHs that played a key role in this selection criteria. The past history of the DCHs provides the quality of the DCH during the previous iterations. There may be a case where the available DCH has a high ranking but is not utilised for the last few iterations, due to its poor quality, which also decreases the reliability of the channel(s).

The range of the R_{DCH} lies from between 0 to 1, where 1 is the highest value and 0 indicates the lowest value. For example, DCHs 1, 2 and 3 have same values (which are 1) but a pair of SUs needs to select only the two most reliable DCHs. The SUs then have to further extend their approach and modify the selection criteria by including PU activity. I have designed the Equation (4.1) indicate that if more than two DCHs have the same value in terms of reliability, then it considers PU occupancy for the selection of the DCHs. Thus, the two DCHs with least PU activity are considered the most reliable DCHs for exchanging the SUs' information.

$$R_{DCH} = \frac{CH_{RANK}}{NT_{CH}^{USAGE} * PU_{OC}^{LEAST}} \tag{4.1}$$

Case III: Equation (4.1) is valid for cases I and II. However, in Case I, the value of the CH_{RANK} and NT_{CH}^{USAGE} is set to 1, due to the initialisation of the CR network. While in Case II, SUs select the reliable DCHs based on the parameters noted in Equation (4.1). The RECR-MAC protocol then selects at least two DCHs, which increase the probability of successful communication among the SUs by adopting novel channel selection criteria. The first reliable DCH is named the "Primary Data Channel 1" (PDC 1) and next reliable DCH is named "Primary Data Channel 2" (PDC 2). If PU returns over the PDC 1 during the communication, then ongoing communication switches to the PDC 2, behaving as a BDC for PDC 1, without renegotiating over the CCH to reduce the overheads, and vice versa. However, if PU returns over the PDCs 1 and 2 simultaneously, then the SUs must re-start the entire process, including scanning, information exchange and communication processing.

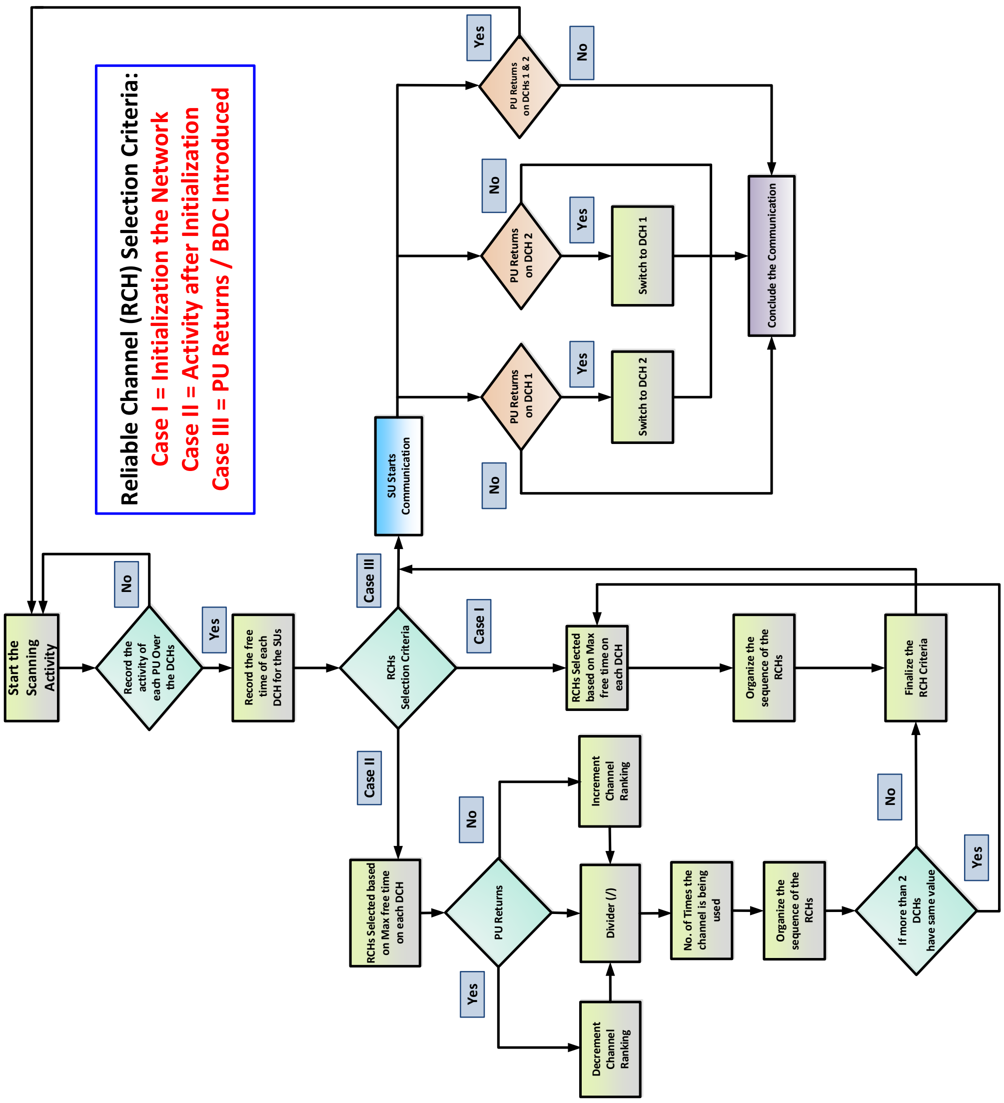

FIGURE 4.8: Reliable channel selection process of the RECR-MAC protocol

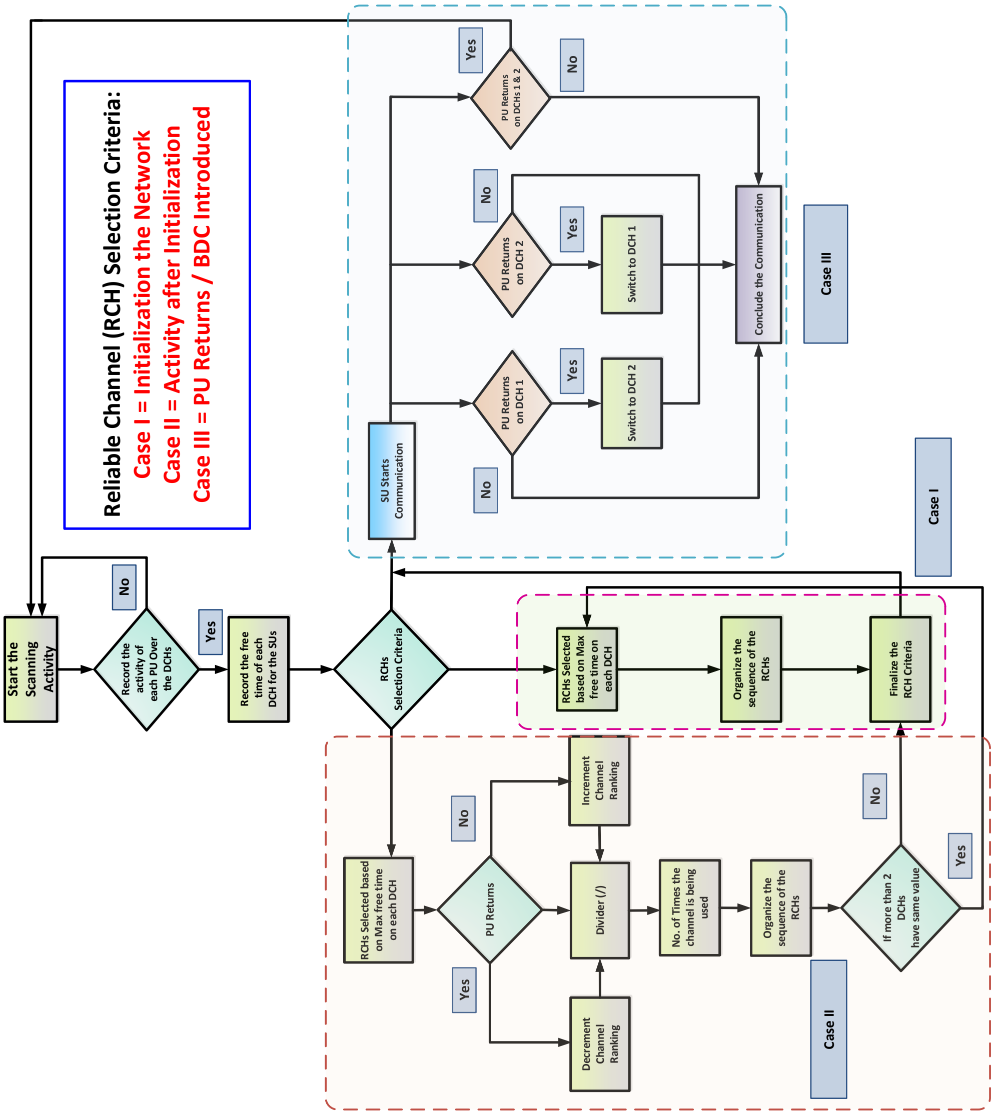

FIGURE 4.9: Reliable channel selection process of the RECR-MAC protocol with cases

4.4 Communication Time Over Control and Data Channels

The key aspect of the CRN is to scan and access the CCH and to advertise the available channel list among the contributing SUs. Successive communication can only take place if the SUs agree to exchange their data frames over the suggested DCHs obtained from the initial dialogue over the CCH. As discussed in Section 3.2, the proposed RECR-MAC protocol performs its operation in four phases: (1) "scanning and accessing the DCCH"; (2) "exchanging the control frames in an efficient and effective way and selecting reliable DCHs"; (3) "exchanging data frames over the selected DCH"; and (4) "continuing the data communication even if the PU returns over the DCH during the communication".

The SUs must exchange control information via DCCH, as this is a prerequisite for any subsequent data communication via DCH. The communication time required over the control and data channels for exchanging control and data information heavily contributes towards the communication time. However, if SU takes longer than expected to exchange the control and data information over its channels, it may reduce the efficiency of the network. Time requirement related to exchanging control and data frames is called 'total communication time'. In this section, the researcher will calculate and compute the total communication time for the RECR-MAC protocol with, and without, PU returns, and then compare this time with other well-known CR-MAC protocols.

Due to the overlay spectrum sharing process, SUs are only able to communicate amongst each other when PUs are not utilising their licensed spectrum bands. It is therefore important to optimise and design the control frames in such a way as to minimise the control frame exchanging time over the CCH (which is considered as an overhead), and keep the maximum time for data communication among the SUs. The proposed protocol has been designed by aiming to reduce communication time over the CCH by: i) optimising the size of the control frames; and ii) reducing the number of handshakes. In addition, it aims to reduce communication time over the DCHs by: i) selecting at least two reliable DCHs; ii) using both selected DCHs for simultaneous transmission; and iii) introducing the BDC, where both selected DCHs are backup to each other if the PU returns on any of the DCH during the communication.

As discussed above, the IEEE 802.11b parameters [143] [144] [20] [23] are used as a benchmark to calculate the communication time among the SUs over control and data channels. The CCH is considered dedicated and always available for SUs. The parameters and their values are used in the proposed protocol and further benchmark CR-MAC protocols shown in Tables 4.1 and 4.2. There are a large number of reasons for selecting the benchmark CR-MAC protocols and their comparison with the proposed RECR-MAC protocol. These include: i) being highly cited; ii) being new; iii) assuming that the CCH is dedicated; iv) exchanging control information prior to data communication; and v) their design and architecture match each other. For example: i) the DSA-MAC protocol uses channel selection criteria; ii) RMC-MAC uses BDC; iii) SWITCH-MAC protocol considers BDC and channel ranking (without considering some critical parameters such as channel quality and history of the used channel); and iv) the classical RTS/CTS and ACK are exchanged over the CCH. However, some additional frames, such as ACK_hello, Emergency Beacon (EB) and Handoff Beacon (HB) are also exchanged over the CCH for the selection of the DCHs.

Multiple data frames with different sizes (such as 1000 Bytes, 950 Bytes and 900 Bytes, respectively) are considered to calculate the total communication time over the control and the data channels. The data rate for the control and data channels is assumed to be 11 Mbps. Equations 4.2 to 4.6 calculate total communication time over the control and data channels when there is no interference and no PU returns during the data communication for the RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols.

$$T_{RECR-MAC} = \left\{ T_{DIFS} + T_{BO} + T_{ACL} + T_{AACL} + \frac{T_{DATA}}{2} + 3 * T_{SIFS} + T_{ACK} \right\} \tag{4.2}$$

$$\begin{aligned} T_{CREAM-MAC} = \{ & T_{DIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{CST} + T_{CSR} + T_{DATA} + 5 * T_{SIFS} \\ & + T_{ACK} \} \end{aligned} \tag{4.3}$$

$$\begin{aligned} T_{DSA-MAC} = \{ & T_{DIFS} + T_{BO} + T_{FRQ} + T_{FRP} + 2 * T_{ACK_{HELLO}} + T_{DATA} + 5 * T_{SIFS} \\ & + T_{ACK} \} \end{aligned} \tag{4.4}$$

$$T_{SWITCH-MAC} = \{T_{DIFS} + T_{BO} + T_{RTS_{SWITCH}} + T_{CTS_{SWITCH}} + T_{NTR_{SWITCH}} \\ + T_{DATA} + 4 * T_{SIFS} + T_{ACK}\} \tag{4.5}$$

$$T_{RMC-MAC} = \{T_{DIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{DATA} + 3 * T_{SIFS} + T_{ACK}\} \tag{4.6}$$

Equations 4.7 to 4.11 calculate the total communication time over the control and data channels when PU returns to the DCH during data communication among the SUs for the RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols.

$$T_{RECR-MAC_{PU}} = \{T_{DIFS} + T_{BO} + T_{ACL} + T_{AACL} + \frac{T_{DATA}}{2} + T_{SWITCH} \\ + T_{DATA} + 3 * T_{SIFS} + T_{ACK}\} \tag{4.7}$$

$$T_{CREAM-MAC_{PU}} = \{2 * (T_{DIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{CST} + T_{CSR} + T_{DATA}) \\ + T_{SWITCH} + 9 * T_{SIFS} + T_{ACK}\} \tag{4.8}$$

$$T_{DSA-MAC_{PU}} = \{2 * (T_{DIFS} + T_{BO} + T_{FRQ} + T_{FRP} + T_{DATA}) + T_{SWITCH} + 5 * T_{SIFS} \\ + T_{ACK} + 3 * T_{ACK_{HELLO}}\} \tag{4.9}$$

$$T_{SWITCH-MAC_{PU}} = \{T_{DIFS} + T_{BO} + T_{RTS_{SWITCH}} + T_{CTS_{SWITCH}} + T_{NTR_{SWITCH}} \\ + 2 * T_{DATA} + T_{SWITCH-MAC} + 4 * T_{SIFS} + T_{ACK}\} \tag{4.10}$$

$$T_{RMC-MAC_{PU}} = \{T_{DIFS} + T_{BO} + T_{RTS} + T_{CTS} + T_{EB} + T_{HB} + 2 * T_{DATA} \\ + T_{SWITCH} + 5 * T_{SIFS} + T_{ACK}\} \tag{4.11}$$

Table 4.2 shows the parameters of the CR-MAC protocols. These values help calculate the total communication time (including the contention, access and exchange of control and data frames) for the proposed RECR-MAC protocol and the benchmark CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols. The description of the CR-MAC protocols and their operations will be discussed in the following section.

TABLE 4.2: CR-MAC protocol parameters and their values

Parameters	**Values(μs)**	**Parameters**	**Values(μs)**
T_{DIFS}	50	T_{ACL}	18.18
T_{BO}	320	T_{AACL}	9.45
T_{SIFS}	10	T_{ACK}	10.18
T_{RTS}	14.54	T_{CTS}	14.54
T_{CST}	14.54	T_{CSR}	14.54
T_{FRQ}	14.54	T_{FRP}	14.54
$T_{ACK_{HELLO}}$	11.64	$T_{CH-SWITCH}$	5
$T_{SWITCH-MAC}$	40	$T_{RTS_{SWITCH-MAC}}$	14.54
$T_{CTS_{SWITCH-MAC}}$	11.64	$T_{NTR_{SWITCH-MAC}}$	11.64
T_{EB}	14.54	T_{HB}	14.54

4.5 Comparison of RECR-MAC and benchmark CR-MAC Protocols based on Timing Diagrams

In this section, communication time over the control and data channels based on Equations 4.2 to 4.11 is calculated to undertake a performance evaluation of the proposed RECR-MAC protocol and other benchmark CR-MAC protocols (CREAM-MAC, DSA-MAC, RMC-MAC and SWITCH-MAC). Moreover, the calculated communication time needs to be compared with other well known protocols [57] [20] [58] [23] without, and with, PU returns over the DCH. The complete evaluation and implementation of the proposed RECR-MAC protocol will be presented in the following chapters. However, the initial analysis of the RECR-MAC protocol is conducted here, based on communication time and energy consumption and comparing results with the CREAM-MAC [23], DSA-MAC [20], SWITCH-MAC [58] and RMC-MAC [57] protocols, using the timing diagram and numerical analysis as shown in Figures 4.10 and 4.11. In order to assist readers, the successful communication time of the proposed RECR-MAC and the timing diagrams are restricted to depicting the behaviour of Equations 4.2 to 4.11. The authors in [143] [144] [20] [23] have adopted the IEEE 802.11b physical characteristic values (as shown in Table 4.2 as benchmark values, in order to calculate the total transceiver time among SUs without, and with, backup DCHs for the

RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols. Equations 4.2 to 4.11 are applicable and valid for any number of SUs.

As discussed in the section above, the CREAM-MAC protocol adopts four-way handshaking over the CCH in order to exchange four frames. The main objective of the four frames is to reserve the CCH, in order to avoid the hidden terminal issues and to avoid collisions between the SU and the PU. The DSA-MAC protocol uses two additional Hello messages along with RTS/CTS, which contain information concerning the SST that includes the ID and SINR of the channel. The objective of the DSA-MAC protocol is to improve spectrum sharing and to notify the neighbouring SUs of the completion time of the transmission to avoid interference among SUs. The SWITCH-MAC protocol uses standard RTS/CTS frames for the ideal conditions. SWITCH protocol utilises additional frame NTR to update the information concerning the BDC to the other SUs within the range. The RMC-MAC protocol uses the standard RTS/CTS for the selection of the DCH for communication among the SUs. The RMC protocol utilises two additional control frames (such as EB and HB) which update the SUs to switch to another available DCH when PU returns to its licensed channel(s).

However, the RECR-MAC protocol has adopted two-way, instead of four-way, handshaking in order to reserve and exchange control information which avoids collisions, traditional wireless problems (named as hidden terminal problems and the multi-channel hidden terminal problems among the SUs), as discussed in Chapter 3. The RECR-MAC protocol also modifies the standard RTS/CTS frames and replaces them with ACL and AACL frames. In addition, the RECR-MAC protocol optimises additional features (such as DCH selection criteria based on the channel ranking and primary and backup data channels information). Thus, the RECR-MAC has integrated additional features into the existing model of the RTS/CTS and replaced them with ACL/AACL without degrading network performance. Further details will be discussed in the following chapter. Figures 4.10 and 4.11 depict the activity of the control frames, primary and backup DCHs and communication time based on Equations 4.2 to 4.11 among the SUs for the RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols both with no PU returns, and with PU returns.

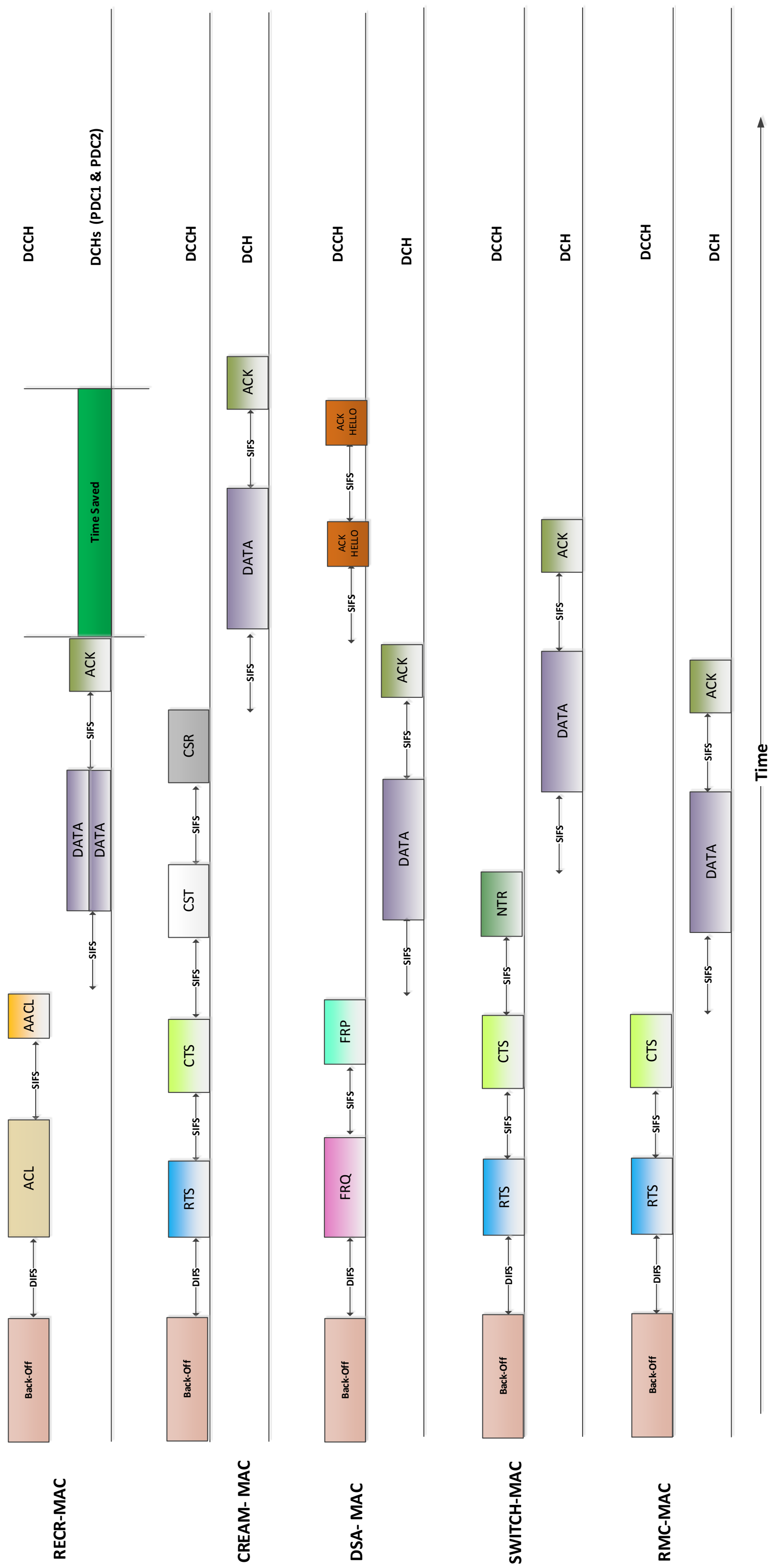

FIGURE 4.10: RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC timing diagram (time saved) without backup data channel

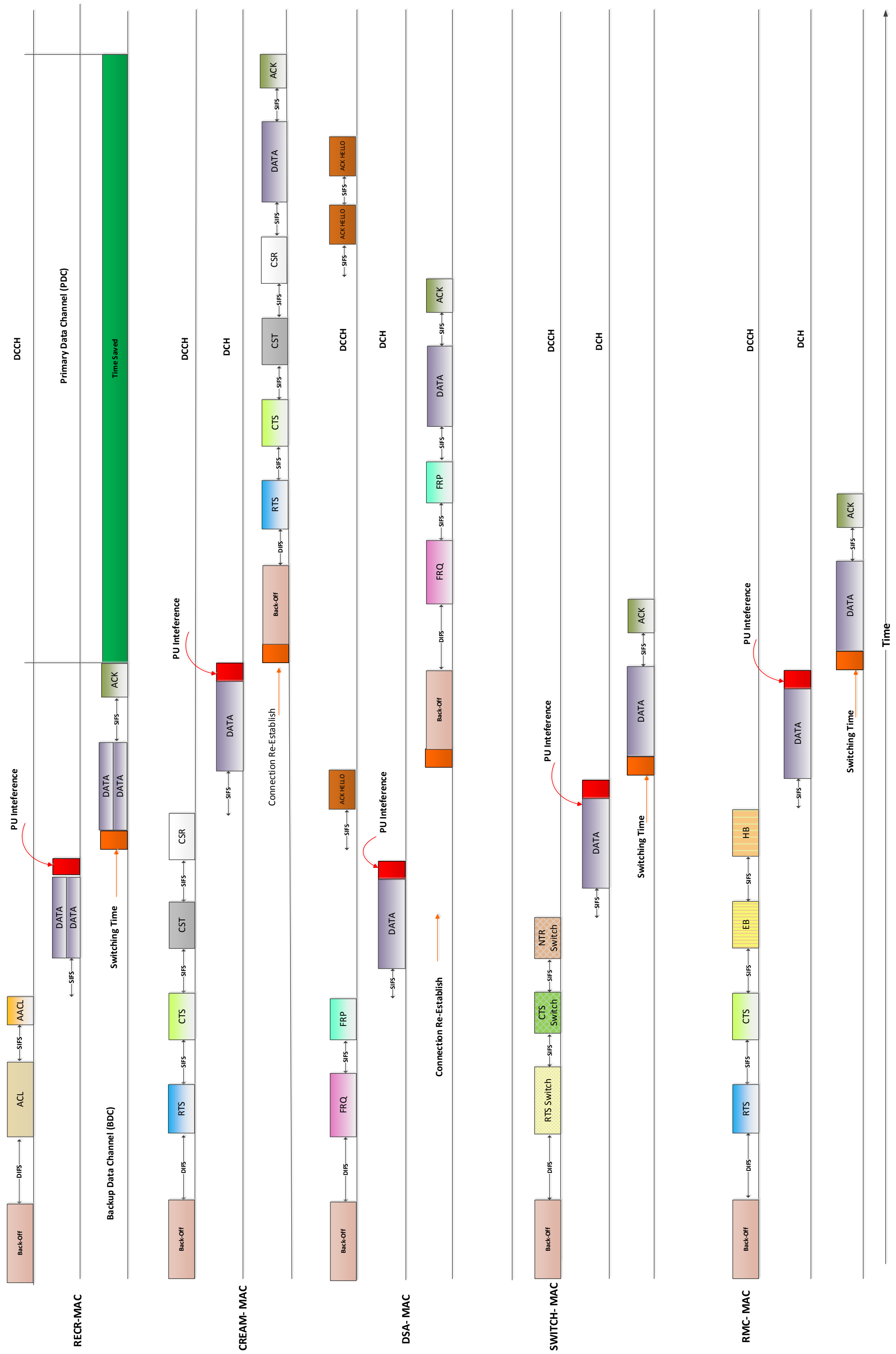

FIGURE 4.11: RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC timing diagram (time saved) with backup data channel

The RECR-MAC and other benchmark CR-MAC protocols have clearly demonstrated the handshaking process over the control and DCHs both with no PU returns and with PU returns. The communication among the SUs in Figure 4.10 has successfully exchanged their control and data information and there are no PU returns over the DCH during the data communication. However, the interference caused by returning the PU over the licensed DCHs in Figure 4.11 demonstrates the communication patterns among the SUs. The CREAM-MAC and DSA-MAC protocols do not use any BDCs, hence both protocols must re-start scanning and re-establishing their connections to complete data communication among SUs. However, this consumes additional time and energy and reduces network throughput. On the other hand, the RECR-MAC, SWITCH-MAC and RMC-MAC protocols have a BDC facility to enable them continue the communication if PU returns. If PU returns during the communication over the DCHs, these three protocols switch to their BDC and resume the communication instead of re-starting the entire procedure, thus saving communication time and energy and increasing network throughput. In the worst-case scenario, if PU returns over the PDC during the communication, and SUs switch to their BDC but PUs already occupy the BDC, then SWITCH-MAC and RMC-MAC protocols restart their communications from the beginning. However, RECR-MAC is capable of handling such situations when PU returns either on the PDC or BDC. For example, if PU returns over the selected DCH1, then the SU's communication requires a switch to the pre-selected DCH2, and vice versa.

Thus, the above timing diagrams clearly demonstrate the importance of the BDC, particularly when the PU returns. RECR-MAC protocol has clearly demonstrated the advantages for the optimisation of the control frames, which has reduced additional handshaking over the CCH. In addition, it has provided the opportunity to the SUs to have additional time over the DCH that allows them an exchange of large amounts of data frames and to successfully conclude their communications.

4.6 Analysis of Communication Time over the RECR-MAC and benchmark CR-MAC protocols under different payloads

This section discusses the effect of different payloads on communication time among the SUs with, and without, BDC. Communication time among SUs is one of the key factors playing a vital role in the performance of the CR-MAC protocols during the communication over the control and data channels. In addition, this factor has a direct impact on the network throughput: for example, higher communication times consume additional energy, increase delay and reduce the network throughput, and vice versa. As discussed in the above chapters, the communication time over CCH is an overhead in the CRAHN. Therefore, each CR-MAC protocol must aim to reduce communication time over the CCH in all possible ways. To overcome this challenge, the RECR-MAC protocol efficiently optimises the control packet, thus reducing the control overheads over the CCH and providing an opportunity to the SUs to have more time over the DCH for communication.

The complete evaluation and implementation of the proposed RECR-MAC protocol will be discussed in the following chapters. However, initial analysis of the RECR-MAC protocol focused on communication time and compared results with the existing benchmark CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols, based on timing diagrams, as shown in Figures 4.10 and 4.11 and Equations 4.2 to 4.11. In order to understand the successful communication time of the proposed RECR-MAC and other benchmark CR-MAC protocols, the timing diagrams are restricted to depict the behaviour of Equations 4.2 to 4.11. The IEEE 802.11b physical characteristic values discussed in Table 4.2 are used to calculate the total transceiver time among SUs without, and with, backup DCHs for the RECR-MAC, CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols, using different payloads of the following sizes: 1000 Bytes, 500 Bytes and 50 Bytes. Moreover, Equations 4.2 to 4.11 are valid for the calculation of the transceiver time for any number of SUs. However, in this section, two SUs are considered in order to calculate the duration of the communication time without, and with, the PUs return over the DCH. Three different sizes of payload are tested in order to understand the behaviour and reliability of the SUs without, and with, PUs returns as shown in Figures 4.12 to 4.13. The proposed RECR-MAC protocol, and the benchmark CR-MAC protocols, have different sizes of payload exchanges among the SUs over the DCHs and the SUs record PU activity during the communication. The results achieved from the

RECR-MAC and other CR-MAC protocols are shown in Figure 4.12. There are different sizes of payloads considered to validate the reliability of the RECR-MAC protocols, and their comparison with other benchmark protocols. Hence, the following results reveal that the RECR-MAC protocol requires less communication time as compared to other CR-MAC protocols for different payloads.

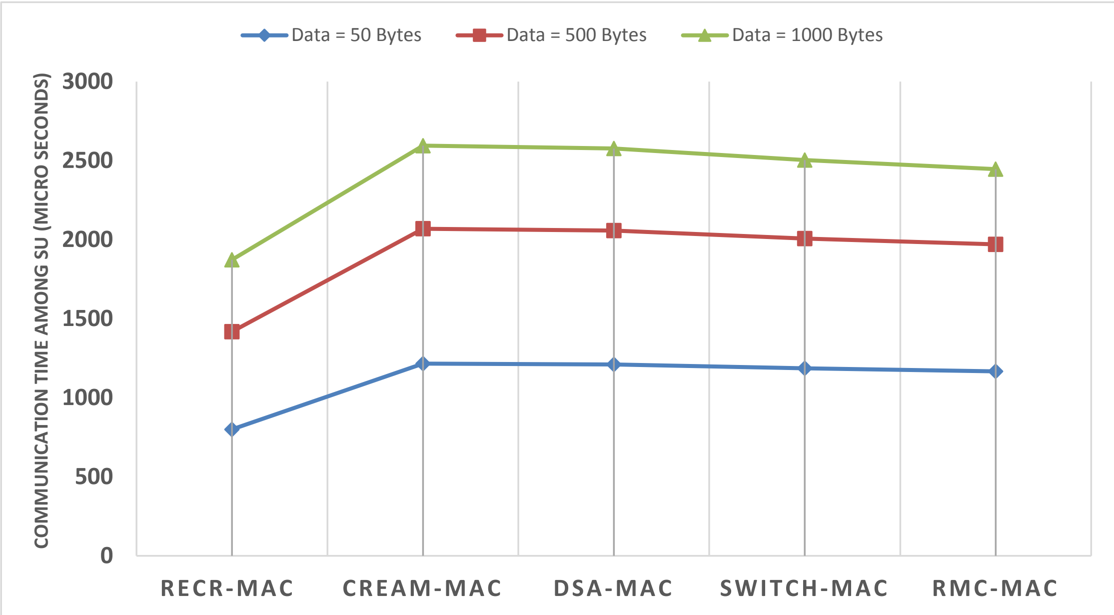

Figure 4.12: Communication Time among SUs (μs) for different payloads without PU returns

Figure 4.13 demonstrates the communication time among the SUs with PU activity during data communication over the DCHs. However, RECR-MAC is able to switch the BDC without re-starting the entire process and for this reason it achieves this in less communication time than the other benchmark CR-MAC protocols.

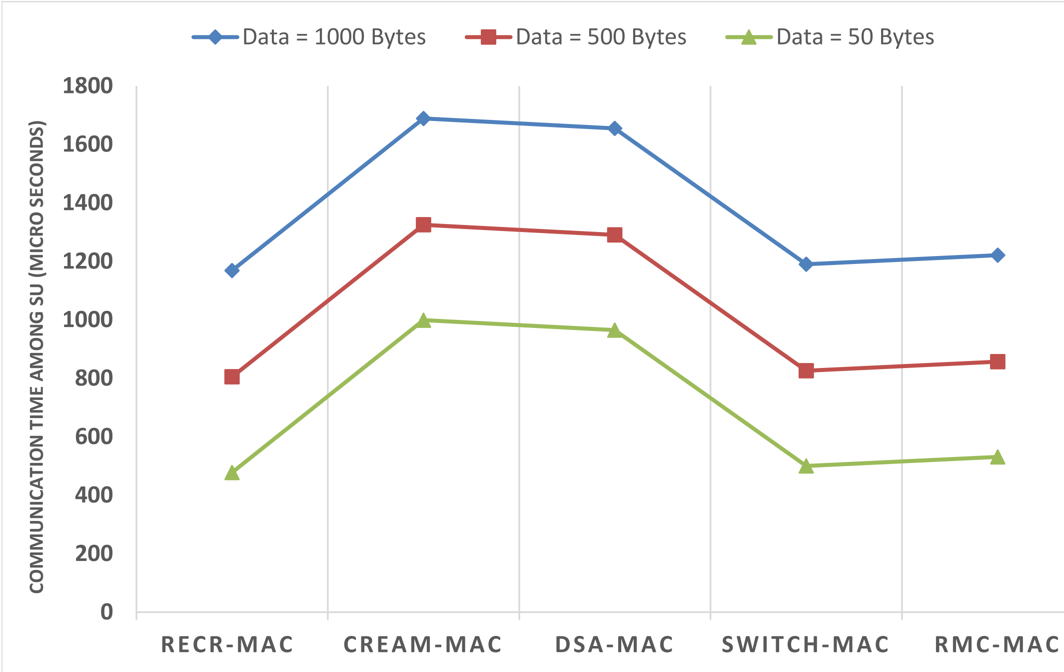

Figure 4.13: Communication Time among SUs (μs) for different payloads with PU returns

Figures 4.12 to 4.13 demonstrate that the reduction of additional handshaking over the CCH, and the introduction of the BDC, assist in reducing communication time among the SUs for the RECR-MAC protocol, as compared to the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols. The CREAM-MAC and DSA-MAC protocols do not have BDCs. Both those protocols therefore begin scanning and re-establishing their connections in order to complete their transmissions. Conversely, the SWITCH-MAC and RMC-MAC protocols adopt a BDC, which helps re-establish the connection during PU returns over the DCH. However, the BDC technique adopted by the RECR-MAC protocol is more efficient and reliable. The RECR-MAC protocol thus utilises the least communication time to exchange data information as compared to other selected benchmark CR-MAC protocols selected for the comparison.

4.7 Summary and Contributions

In summary, this chapter presented the discussion of the impact of DCH selection process and BDC for the proposed RECR-MAC protocol. In addition, the CR-MAC protocols have been classified into four groups with an in-depth analysis of each protocol and its shortcomings. The comparison of the random channel selection technique and selection of the channel with the criteria has been classified into three phases: these discussed the disadvantages of random channel selection criteria and the importance of reliable channel selection criteria. The researcher has seen no evidence to suggest that efficient and reliable DCH selection and BDC simultaneously has yet been adopted elsewhere, where both DCHs are backups for each other if PU returns on any of the DCH during the communication. Moreover, the selection criteria of the DCHs are based on multiple factors. These include: 1) selection of reliable DCHs based on the maximum free time recorded by the SUs over the DCH followed by; 2) channel ranking, which is proportional to the number of positive/negative acknowledgements and past history of the DCHs. If more than two DCHs have equal value during the second, third and following iterations, then the DCHs are selected based on the maximum free time. The priorities of the DCHs are assigned on the basis of RDCH 1, RDCH 2, RDCH 3, and RDCH 4, respectively (where RDCH 1 and RDCH 2 have the highest priority, RDCH 3 and RDCH 4 have the next priority, and so on). The communication time has been calculated based on the timing equations for the RECR-MAC and benchmark CR-MAC protocols. Thus, timing analysis demonstrates that the reduction of additional handshaking over the CCH, and the introduction of the BDC, assist in the reduction of the communication time among the SUs for the RECR-MAC protocol, as compared to the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols. The next chapter presents the energy and throughput analysis of the RECR-MAC protocol.

Chapter 5

Energy and Throughput Analysis of the RECR-MAC Protocol

This chapter will analyse in detail the performance of the Reliable and Energy Efficient Cognitive Radio Multi-Channel Medium Access Control Protocol for Adhoc Networks (RECR-MAC). This is based on communication time, transmitted energy, throughput and delay for the saturation network, where the SUs always have data to exchange over the DCH with multiple sizes of payload. A new data frame is available to each SU once the last data frame has been transmitted successfully [145] [23]. Therefore, the SUs are continuously seeking unused spectrum bands for communication. In contrast, the SU may have a vacant queue in a non-saturation network [146].

In order to make the model realistic, the CRN co-exists with PUs by utilising the same spectrum bands, and the number of PU pairs is equal to the number of licensed channels, as shown in Figure 3.1. However, the number of SUs and the data to be transmitted may vary. Without a loss of generality, the frames related to the SU arrive according to a Poisson process. The PUs are able to use their licensed channels and follow the independent and identical ON/OFF renewal process. The ON state indicates the presence of the PUs and the OFF state indicates the absence of the PUs. In contract, when it comes to the SUs, the ON state indicates that there is no opportunity for the SUs to utilise the licensed channel and the OFF state indicates that there is an opportunity for the SUs to utilise and exchange their data information. Each SU has a sensor [147] to record the activity of the PUs while its transceivers are busy exchanging the information over the DCHs. The function of the sensor is to sense the PU returns and update the SU to switch to another channel, called a BDC. Moreover, the RECR-MAC protocol assumes that the CCH is always available and dedicated for the SUs to exchange their control information.

As shown in Figure 3.1, each SU has two transceivers (TX1/RX1 and TX2/RX2) and a sensor which records both the free time and the PU returns. A1 and B1 represent the transmitters of SU1, and A2 and B2 are the receivers of SU2 and Channel 1, Channel 2, etc. represent the DCHs. The data frames split into two parts and are transmitted over two DCHs simultaneously, as discussed in Chapter 3. The ACK is generated by the receiver of SU2, after completion of the data received from SU1. The SUs are unable to transmit data until a minimum of two DCHs become available for communication to enhance the chance of continuous data transmission for the RECR-MAC protocol. Moreover, the SUs consume energy at each layer to exchange control and data frames, as shown in Figure 5.1. However, if the number of re-transmissions could be reduced and BDC introduced to continue the communication when the PU returns, this would save a significant amount of transmitted energy over the MAC layer as compared to any other layers.

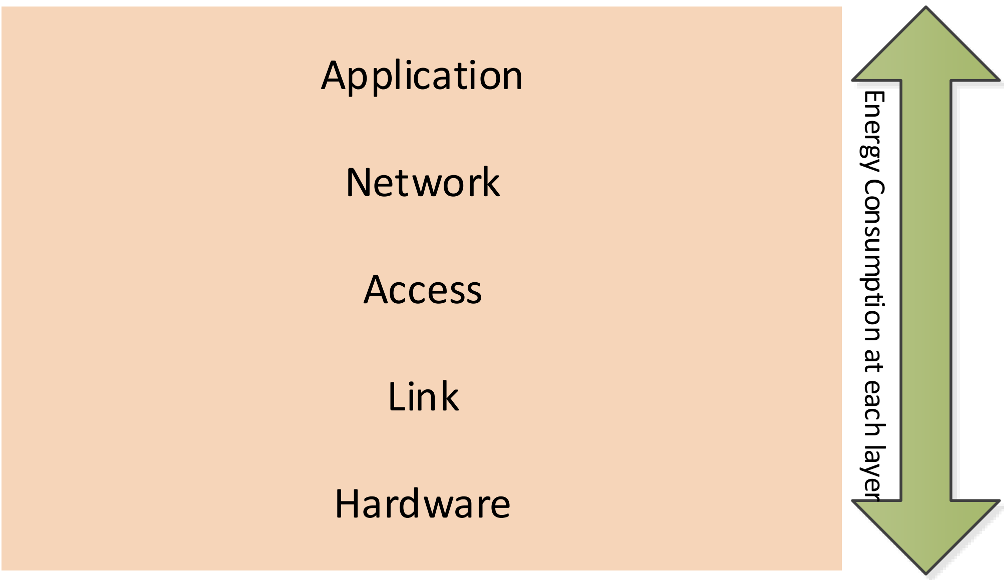

FIGURE 5.1: Energy consumption at each layer

The next section discusses the characteristics of the RECR-MAC protocol and its comparison with other selected benchmark protocols, such as the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols.

5.1 Importance of Energy Saving for RECR-MAC

2% of all energy consumed globally is utilised by information technology and 0.5% is consumed by wireless technology [148]. Between 2006 and 2014, there has been 92% growth in wireless technology [149]. The Wireless World Research Forum has forecasted that 7 trillion wireless devices will serve 7 billion people by 2017 [150]. Luent technology and other energy efficient CR-MAC protocols [151] [148] [152], indicate that the utilisation of the transmitting energy is higher (or sometimes double) that of the receiving energy for any data size of the wireless network.

The authors in [153] [154] [155] also believe that a large amount of energy is consumed during the processing and transmitting activity of the SUs. The processing energy is consumed by the detection of the free time over the CCH, and other signal processing activities, before the communication begins. There are multiple techniques used to minimise energy consumption at the MAC layer, which have been discussed in [24] [156] [154] [21] [25] [155]. It is to be noted that the unnecessary control frames handshakes over the CCH, and the large number of retransmissions over the DCHs, utilise large amounts of transmitted energy in the CRAHNs. The consumption of unnecessary transmitted energy decreases the efficiency of the network.

5.2 Impact of Contributing Factors over the Energy Consumption for RECR-MAC

As discussed above, it is important to design the proposed RECR-MAC protocol to use less transmitted energy. There now follows a discussion of the contributing factors to reducing the transmitted energy in the cognitive network, and making the RECR-MAC protocol an energy efficient protocol:

5.2.1 Reducing Number of Handshaking over Control and Data Channels

The successful exchange of the control information permits the SUs to start the communication over the DCHs. However, the situation is critical if the SUs are unable to exchange their control information, which requires restarting the control process. As previously discussed, some protocols utilise additional handshaking over the control and data channels to avoid the restarting process. For example, some CR-MAC protocols (such as CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC) require 4 or 6 or more numbers of control and data frames in order to exchange their information. The additional number of control and data frames requires a greater number of handshakes over the control and data channels, which requires extra transmitting time to process these frames. This consumes additional transmitted energy. Furthermore, the SWITCH-MAC and RMC-MAC protocols require additional handshaking if the PU returns over the DCH during the data communication. Therefore, the framework of the RECR-MAC protocol has been designed to overcome the existing shortcomings without degrading the reliability and effectiveness of the proposed protocol. The RECR-MAC protocol has introduced two-way handshaking over CCH, and two-way handshaking over DCH, irrespective of whether the PU returns or not during the communication. The benchmark CR-MAC protocols and their communication time based on Equations 4.2 to 4.11 are compared with the RECR-MAC protocol. Figures 5.3 and 5.4 demonstrate the benefits of reducing the number of handshakes over the control and data channels.

5.2.2 Minimising the Size of Control Frames

Based on the above discussion, it is important to optimise the control frames by avoiding and reducing unnecessary fields. The optimisation of the control frames in a smart manner requires reducing the communication time among the SUs. This has a direct impact on the energy consumption in the CRAHNs, as shown in Figure 5.2. In Chapter 4, the timing diagrams of the RECR-MAC and benchmark protocols without, and with, BDC depict the effect of minimising the size of the control frames. Moreover, the following section of the numerical example of the performance evaluation reveals the benefits of saving transmitted energy based on reducing the size of the control frames.

The operation of benchmark CR-MAC protocols provides more or less similar functions, including avoiding collisions and the hidden terminal problem, high throughput, re-establishing the connection if PU returns, etc. The RECR-MAC protocol efficiently designs the control frames to handle collisions and hidden terminal problems, and to reduce re-transmission based on channel selection criteria. It also consumes the least communication time between the SUs over the control and data channels, thus saving transmitted energy.

To conclude; by reducing the size of the control frames less communication time is required among the SUs in order to exchange the control information over the CCH, eventually saving greater amounts of energy in the CRAHNs.

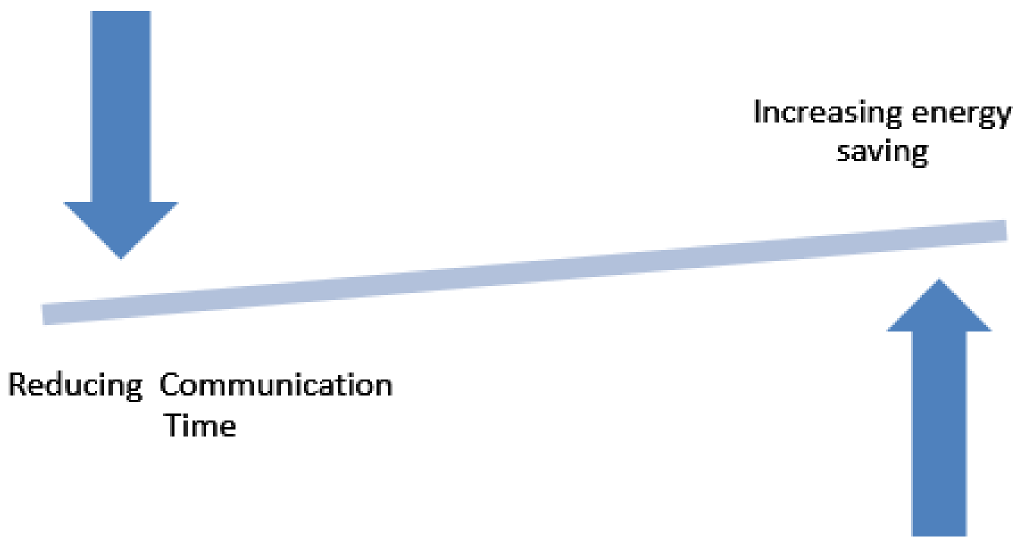

Figure 5.2: Relation of communication time vs. energy saving

5.2.3 Reducing Re-Transmission among SUs

The aim of CR technology is to enable the SUs to select and utilise the spectrum bands not in use by the PUs. If the PU returns to its licensed channel, then the SU switches to an alternative available channel without any interference to the PU. The majority of the CR-MAC protocols discussed in the literature review are unable to address the re-claiming of the PU along with the restarting the searching and scanning of the other available spectrum bands and retransmission over the control and data channels. This significant feature of the CR-MAC protocol has not been intensively researched. It is a procedure that not only consumes additional time, but also utilises additional energy due to the re-transmission of the control and data frames.

As discussed earlier, the selected characteristics of the RECR-MAC protocol provide an advantage lacked by other CR-MAC protocols. The RECR-MAC protocol introduces the channel selection criteria, which selects reliable channels with the least PU activity in order to minimise the probability of interference between the SUs and PUs. In addition, the RECR-MAC protocol is able to effectively deal with the return of the PU over the licensed spectrum band and re-establish the SUs communication without re-starting the entire process. Selecting the reliable channels, and switching to the BDC if PU returns, saves additional energy and reduces the wait time of the SUs to exchange their information. Thus the effective framework and design of the RECR-MAC protocol provide an opportunity for the SUs to initiate their communication in the CRAHNs, and if any PU returns over the DCH, the BDC is available to avoid re-transmission. Therefore, CR technology requires the RECR-MAC protocol features in order to avoid the search for the free channel and additional re-negotiations over the control and data channels.

5.3 Analysis of Energy Saving between RECR-MAC and Benchmark CR-MAC

As discussed in the sections above, the CR network consumes high transmitted energy when compared to the processing and receiving energy. The focus of this thesis is therefore to reduce the transmitted energy (E) consumption of the RECR-MAC protocol, then compare this with other benchmark CR-MAC protocols (such as CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC) over the control and data channels. The transmitting energy is calculated by using Equations 5.1 and 5.2 for the RECR-MAC and benchmark protocols without, and with, BDC.

$$E_{without\_PU\_Return} = \int_0^{T1} P_1(t)\, dt \tag{5.1}$$

$$E_{with\_PU\_Return} = \int_0^{T2} P_2(t)\, dt \tag{5.2}$$

where T1 and T2 are the total communication times of RECR-MAC and other benchmark CR-MAC protocols over control and data channels without and, with a BDC, respectively. The values of P_1 and P_2 represent the power consumed during the transmission of control and data channels without, and with, a BDC. The total communication time of each protocol is calculated based on the physical layer parameters, as discussed in the previous chapter. The transmitted power of each SU is set to 100 mW [151]. The average transmitted energy is calculated for each protocol without, and with, BDC based on the values as summarised in Tables 5.1 and 5.2.

TABLE 5.1: Communication time of CR-MAC protocols without BDC (μs)

	1000 B	**500 B**	**50 B**
$T_{RECR-MAC}$	800	618	455
$T_{RECR-MAC}$	1216	853	526
$T_{DSA-MAC}$	1210	847	520
$T_{SWITCH-MAC}$	1186	821	496
$T_{RMC-MAC}$	1167	803	477

TABLE 5.2: Communication time of CR-MAC protocols with BDC (μs)

	1000 B	**500 B**	**50 B**
$T_{RECR-MAC}$	1169	805	478
$T_{RECR-MAC}$	1689	1325	999
$T_{DSA-MAC}$	1655	1291	965
$T_{SWITCH-MAC}$	1190	826	500
$T_{RMC-MAC}$	1221	857	531

The analytical results obtained by using Equations 5.1 and 5.2, and the values of Tables 5.1 and 5.2 are depicted in Figures 5.3 and 5.4 with, and without, BDCs. The average energy consumed by RECR-MAC protocol is less when compared with other benchmark CR-MAC protocols with a payloads of 1000 bytes, 500 bytes and 50 bytes respectively. In Figure 5.4, the obvious reason for this difference in energy utilisation is based on the optimisation of the number of control frames and the selection of reliable DCHs.

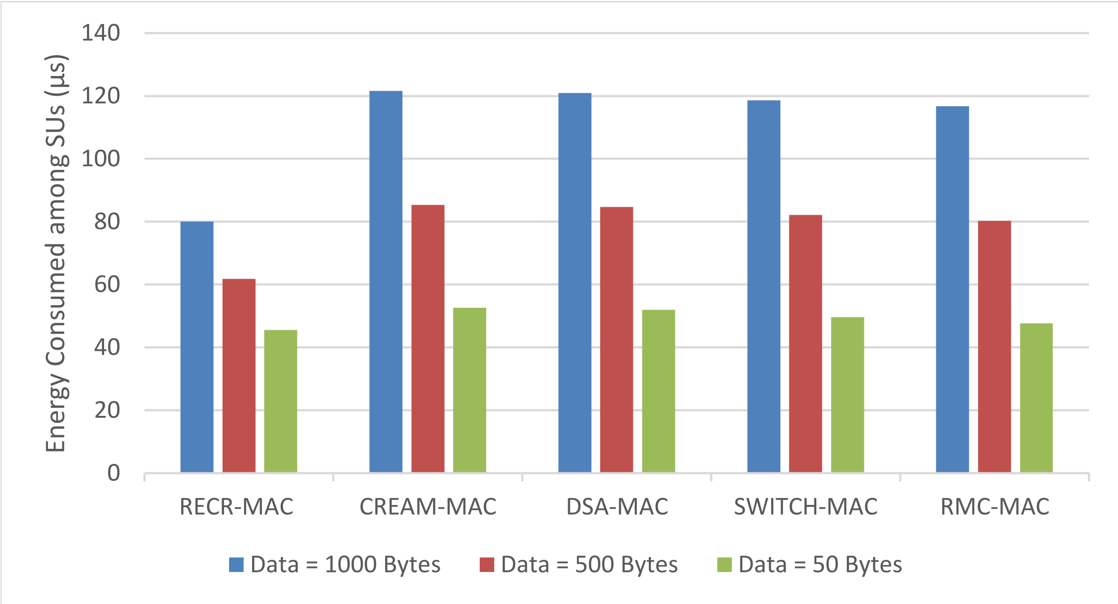

FIGURE 5.3: Energy consumed among SUs (μs) for Data = 1000, 500, 50 Bytes (No PU returns)

Moreover, by the introduction of the BDC, the RECR-MAC protocol does not need to re-establish the entire process and saves increased transmitted energy when compared to other benchmark CR-MAC protocols with a payload of 1000 bytes, 500 bytes and 50 bytes as shown in Figure 5.4. Multiple experiments have been conducted with different sizes of data in order to validate the performance of the RECR-MAC protocol and its comparison with other selected benchmark CR-MAC protocols.

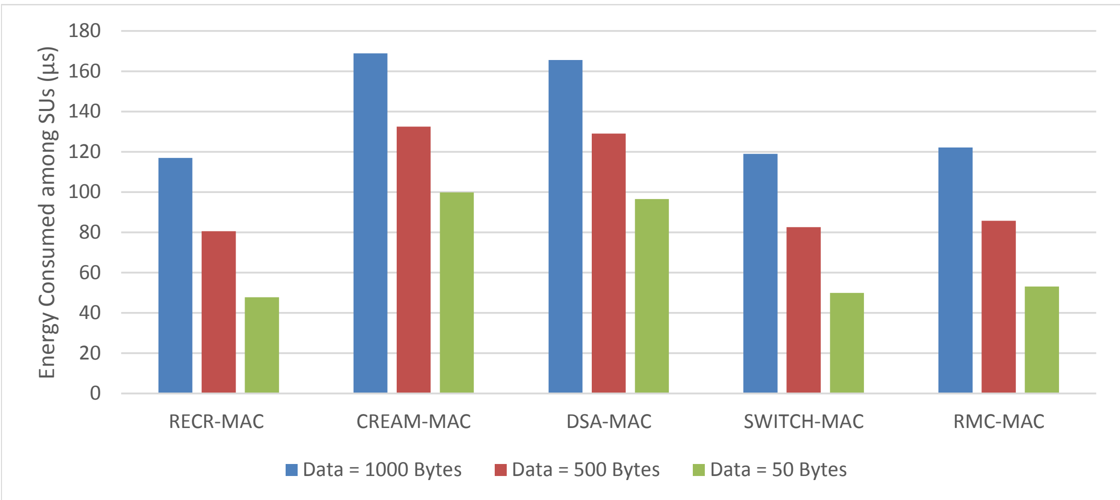

FIGURE 5.4: Energy consumed among SUs (μs) for Data = 1000, 500, 50 Bytes (PU returns)

The results in Figures 5.3 and 5.4 validate the proposition that the proposed framework of the RECR-MAC protocol is applicable for multiple sizes of payloads. The energy consumption during the transmission of control and data information proves that the RECR-MAC protocol is an energy efficient protocol and an useful contribution in the area of CR technology. Moreover, the framework of the RECR-MAC protocol is suitable for developed countries where energy saving is a major challenge, and performs in an effective and efficient way compared to the other benchmark CR-MAC protocols adopted for the purposes of comparison. Thus it concludes that the introduction of the optimisation of the control information and BDC techniques helps to utilise less energy during the transmission of the data over the control and data channels, as compared to other CR-MAC protocols.

5.4 Impact of Contributing Factors over the Performance of Throughput for RECR-MAC

Throughput is another contributing factor to the analysis of the performance of the RECR-MAC protocol in the CRAHNs. In related studies, the majority of researchers have discussed and computed throughput: it is described as the average rate of successful data delivery over a wireless channel, i.e. “data transmitted per unit time”. However, the throughput can be affected by multiple factors during the exchange of control and data information. These include; the availability of the CCH; the probability of access to the CCH; the number of handshakes over the control and data channels; the size of the control frames; the selection criteria of the DCHs: the available number of DCHs with respect to the number of SUs; the number of successes and failed acknowledgements; the ON/OFF time of the PU returns. In this thesis, the communication time among the SUs plays a vital role and directly impacts the performance on the CRAHNs in terms of energy consumption and throughput. If SUs take more than the expected communication time, then this decreases the efficiency of the CRAHNs in terms of energy consumption and throughput of the network. The throughput of the proposed RECR-MAC protocol can be affected by multiple parameters, as shown in Table 5.3. These parameters are directly related to each other and may increase and decrease the throughput of the RECR-MAC protocol. For example, the number of re-transmissions increases the communication time, which eventually contributes to the delay. The probability that the SUs are unable to continue the communication if PU returns also increases delay and decreases overall throughput of the CRNs.

5.4.1 Minimisation of Channel Switching among SUs

The process of channel switching among SUs plays a vital role in the performance of the CRN. Frequent returns of PUs and the selection of bad quality channels requires a high number of re-connections among the SUs in order to accomplish the task. High numbers of re-connections maximizes the rate of the channel switching and consumes significant time for the successful exchanging of control and data frames. The high communication time consumes large transmitted power among the SUs, which reduces network throughput [157]. However, RECR-MAC channel selection criteria overcome this issue by selecting reliable primary and backup data channels, which may require less (or even no) channel switching activity.

5.4.2 Secondary Users Transmission Probability

CR technology is an opportunistic technology. The probability that the SUs can transmit over the control and data channels therefore heavily contributes to the performance of the CR-MAC protocols, including communicating time, energy consumption, delay and throughput. In a contention based CR environment, all SUs share the same medium to be transmitted. Therefore, there is competition among all participant SUs to win the medium. A large number of SUs may increase the probability of collision amongst each other in the CRAHNs. In the RECR-MAC protocol, the channel access scheme by SUs is based on the IEEE 802.11 MAC protocol. The SUs only begin transmitting after an idle period equal to the Distributed Inter Frame Space (DIFS). If a channel is occupied by another SU, the participating SU randomly selects a backoff interval from 0, W-1, where W represents the size of the Contention Window (CW). The value of the CW is taken from the set: 16, 32, 64, — 512. For simplicity, the value 32 is used for the numerical and simulation purposes. There is a probability that SUs may collide during the contention process. It is an important to consider that the PU always has higher priority than the SUs, based on their right to use the licensed channel any time, even though communication is continuing among the SUs. It is also considered that each SU always has the information to transmit at any time. The probability of collision during the contention process for accessing the CCH among SUs has been derived from

[158] as follows:

$$P_c = \left(1 - \frac{1}{CW}\right)^{NSU_S - 1} \tag{5.3}$$

where P_c is the probability of collision and NSU_s represents the number of SUs attempting to access the CCH. It is the standard process in IEEE 802.11b that a large number of SUs increases the probability of a collision. The size of the CW increases to the maximum value denoted as CW_{max}. Based on Equation 5.3, the probability that the SUs may not collide among each other and successfully access the DCCH can be represented as:

$$P_s = 1 - \left(1 - \frac{1}{CW}\right)^{NSU_S - 1} \tag{5.4}$$

where P_s is the probability of successful access to the CCH by the SUs.

5.4.3 Additional Contributing Factors

There are multiple additional factors that influence the performance of RECR-MAC protocol. There is always a trade off among the multiple factors while designing the framework of a CR-MAC protocol. This leads to the researcher having to compromise between factors, according to the design and requirements, including: channel quality; primary and backup data channels selection criteria; communication time; energy saving; delay; number of transceivers; number of control and data channels; hardware costs; throughput, etc. The following are the contributing factors in the RECR-MAC protocol and its relationship with throughput.

a) Number of Transceivers: The number of transceivers can be represented as $T_x R_x$. Additional transceivers transmit additional data, which eventually increases network throughput.

b) Number of Data Channel(s): The Number of Data Channels can be represented as DCH(s). Transmitting over multiple DCHs simultaneously decreases transmission time and signal power and increases the transmission rate of data, also increasing network throughput.

c) Payload: Payload can be represented as P_L. A larger amount of data to be transferred across the multiple DCHs increases the network throughput as compared to other CR-MAC protocols. If the PU returns during the communication, the PDC's data switches to BDC and continue the communication instead of re-start the entire process.

d) Data Rate: Data rate can be represented by D_{Rate}. The D_{Rate} for the control and data channels is set to 11 Mbps as constant.

e) Probability of Successful Access of Dedicated Control Channel: The probability of successful access of DCCH can be represented as P_s. Higher probability of successful completion of the frames over the DCCH will result in faster initialisation of data communication. Faster network initialisation reduces communication time and increases network throughput.

f) Number of Secondary Users: The Number of SUs can be represented as NSU_s, where n represents the number of SUs. Additional SUs contending for the CCHs may reduce the chances in order to seize the opportunity for accessing these channels.

g) Communication Time: Communication time during the control and data channels can be represented for each protocol such as $T_{(RECR-MAC)}$ for RECR-MAC protocol, $T_{(CREAM-MAC)}$ for CREAM-MAC, respectively. Higher communication time decreases network throughput, and vice versa.

h) Probability of False Alarm: Probability of false alarm can be represented as P_{FA}. Minimising the value of P_{FA} provides the maximum opportunity for the SUs to access the spectrum and improves network reliability by selecting unoccupied and reliable channel(s). The value of the probability of false alarm is set to 0.1 as a constant. The detail of the P_{FA} will be discussed in Section 6.2.

The above factors from a) to e) are directly proportional to the network throughput. The above factors from f) to h) are inversely proportional to the network throughput.

5.5 Throughput Analysis of the RECR-MAC with Benchmark CR-MAC Protocols

In this section, an analytical model is developed based on the contributing factors above to analyse the throughput of the RECR-MAC protocol with benchmark CR-MAC protocols under the saturation condition. It is noted that the concept of CR was introduced to manage communication among the devices without licensing, due to the unavailability of the licensed spectrum. Therefore, consideration of the saturation condition is a valid assumption in this thesis for the CRAHNs. If each SU is equipped with a sensor and two transceivers, the RECR-MAC protocol is capable of reserving a number of free channels and utilising them effectively according to the number of SUs in the network. The throughput for the SUs is denoted by η. Moreover, two cases are considered during the calculation of the throughput for the CRAHNs: i) Throughput analysis without PU interference; and ii) Throughput analysis with PU interference.

5.5.1 Throughput Analysis without PU Returns

The interference generated by the return of the PUs heavily contributes to the performance of the CRAHNs. The SUs observe the activity of the PUs, then select the most reliable DCHs based on the channel selection criteria, then effectively utilise the free time for their communication. For the convenience of presentation, Table 5.3 lists the contributing parameters for the throughput analysis of the RECR-MAC protocol and its comparison with other benchmark CR-MAC protocols.

In Equation 5.5, throughput is directly proportional to number of transceivers, DCHs involved in the communication among the SUs, payload, data rate of the channel, and the probability of no collision among the SUs for accessing the CCH.

$$\eta \propto T_x R_x * DCHs * P_L * D_{Rate} * Ps \tag{5.5}$$

TABLE 5.3: Parameters for the throughput analysis of RECR-MAC protocol

Parameters	**Proportionality and Notations**	**Relations with Throughput**
Number of Transceivers	$\propto T_X R_X$	Additional transceivers transmit added data, so increasing network throughput.
Number of Data Channels	$\propto DCHs$	Transmitting over multiple data channels simultaneously increases the throughput.
Payload	$\propto P_L$	Larger amounts of data across multiple data channels increases throughput.
Data Rate	$\propto D_{RATE}$	Higher data rates allow large amounts of data to be transmitted, increasing network throughput.
Probability of Successful Access of Control Channel	$\propto P_S$	Higher probability of successful completion increases network throughput.
Number of Secondary Users	$\propto \frac{1}{NSU_s}$	Increased numbers of SUs contending for the control channels may reduce the chance to seize an opportunity to access the control channel, so reducing network throughput.
Communication Time	$\propto \frac{1}{T}$	Higher communication time decreases the network throughput, and vice versa.
Probability of False Alarm	$\propto \frac{1}{P_{FA}}$	High probability of a false alarm provides the minimum opportunity to the SUs to access the spectrum, which decreases the network throughput.

In Equation 5.6, throughput is inversely proportional to the number of contributing SUs, total communication time of each protocol and probability of a false alarm.

$$\eta \propto \frac{1}{NSU_S * T_{CR-MAC} * P_{FA}} \tag{5.6}$$

Equation 5.7 calculates the throughput for different numbers of SUs without PU returns for the RECR-MAC and benchmark CR-MAC protocols, where payload set as 1000B, 500B and 50B as shown in Figures 5.6 to 5.8.

$$\eta \propto \frac{T_x R_x * DCHs * P_L * D_{Rate} * Ps}{NSU_S * T_{CR-MAC} * P_{FA}} \tag{5.7}$$

As discussed in Chapters 2 and 3, the value of P_{FA} is never equals zero. Figures 5.5 to 5.7 demonstrate that the throughput value changes with different numbers of SUs. When there are only two SUs participating in the CRAHNs for their communication, then a high throughput is achieved, due to less competition among the SUs to access the CCH. In addition, this is expected due to the fact that when there are high numbers of SUs contending for CCH there are fewer chances to seize the opportunity.

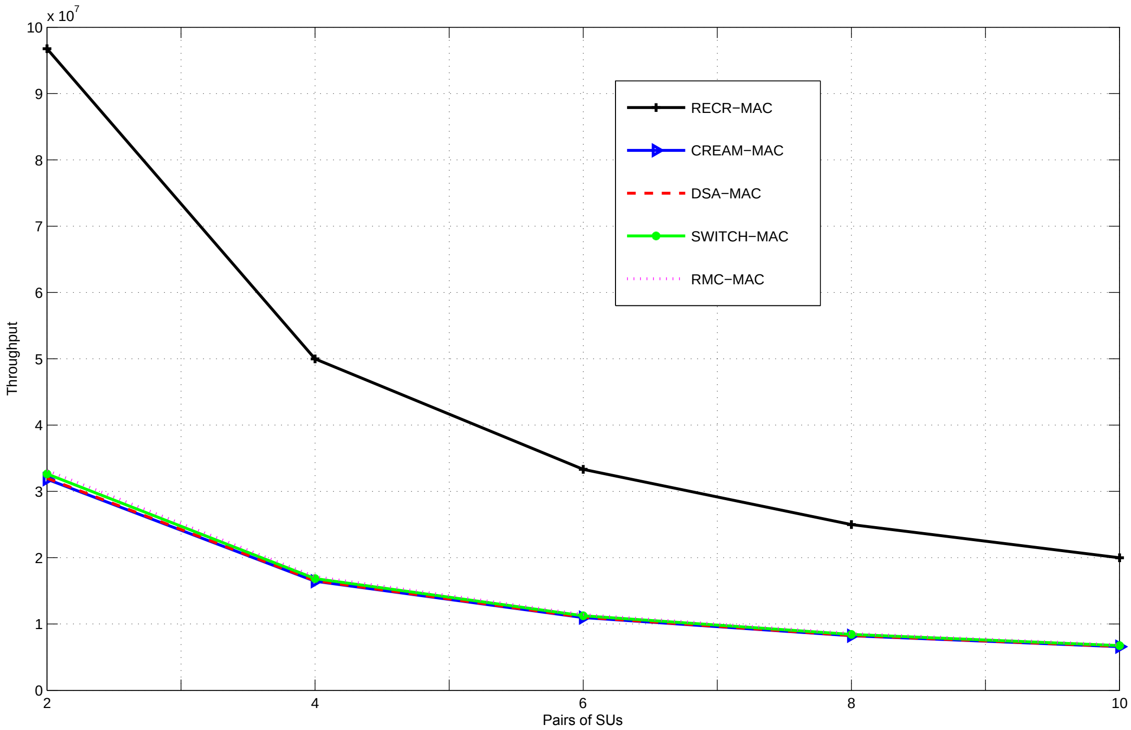

FIGURE 5.5: Throughput vs. Pairs of SUs for Data = 1000 Bytes (No PU returns)

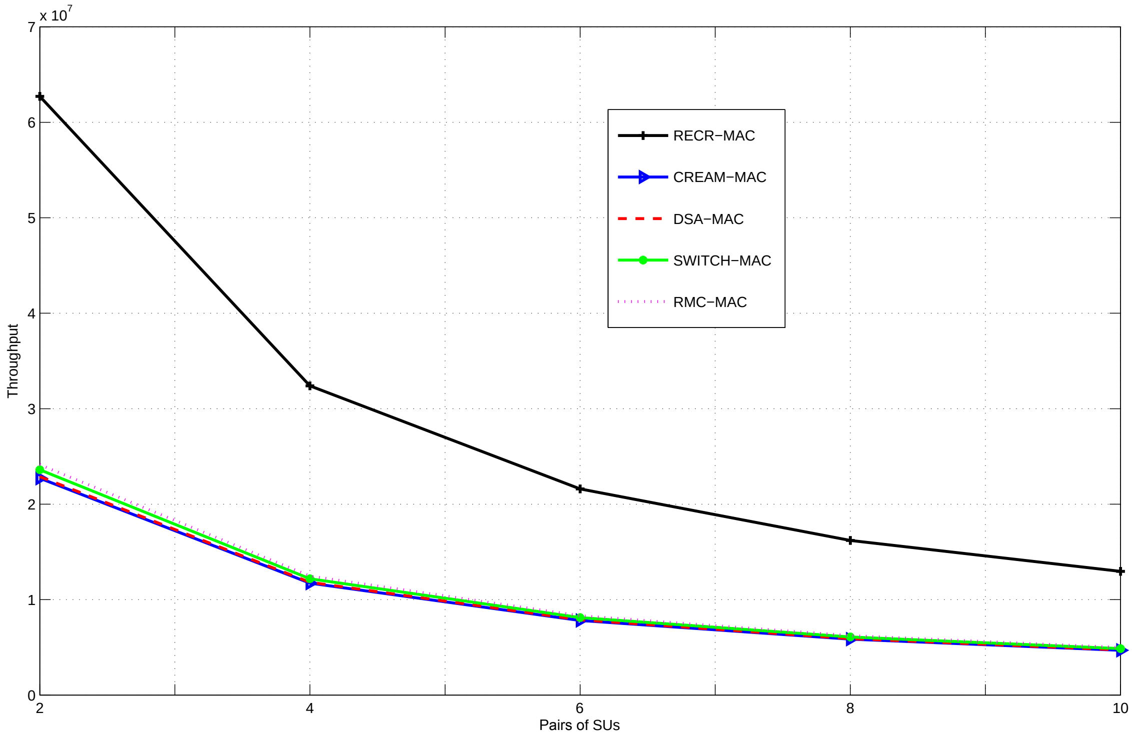

FIGURE 5.6: Throughput vs. Pairs of SUs for Data = 500 Bytes (No PU returns)

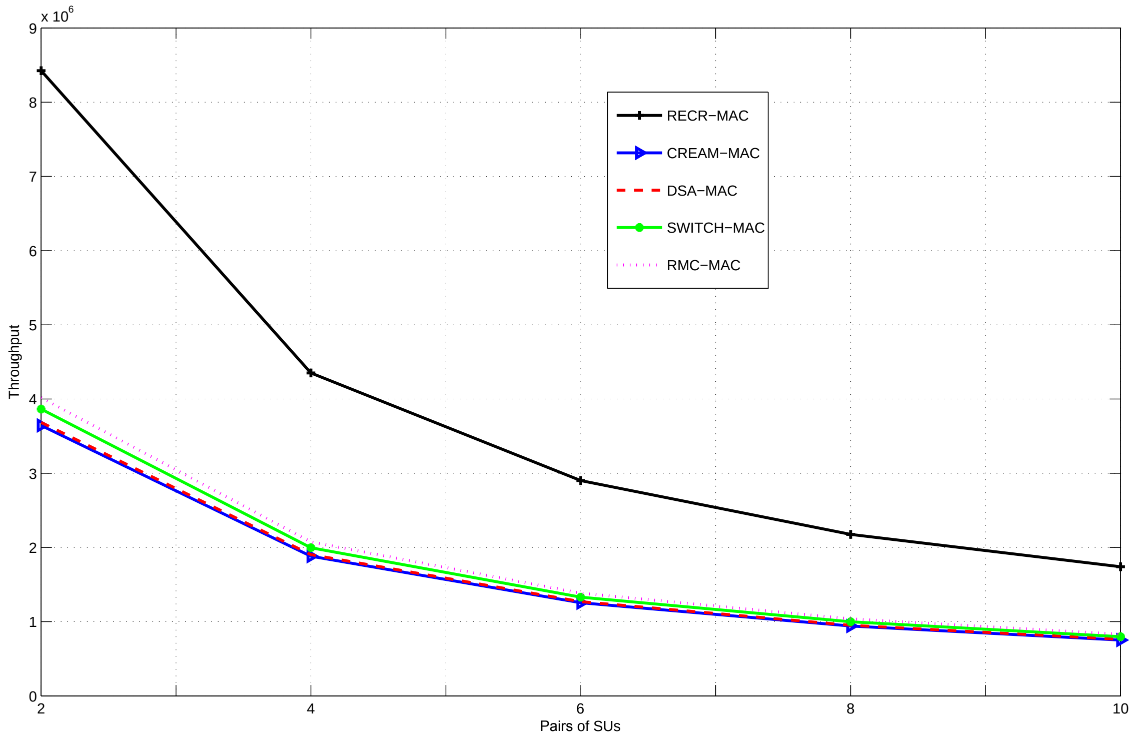

FIGURE 5.7: Throughput vs. Pairs of SUs for Data = 50 Bytes (No PU returns)

5.5.2 Throughput Analysis with PU Returns

As discussed in sub-section 5.5.1 above, the frequent PU returns during the communication heavily reduce the performance of the CRAHNs. To overcome PU interference, the BDC is introduced for the proposed RECR-MAC protocol, which re-establishes the connection among the SUs if the PU returns to its licensed DCHs during the communication. Table 5.2 is also utilised for the analysis of the RECR-MAC protocol and its comparison with other CR-MAC protocols based on Equation 5.7 with different payloads. Figures 5.8 to 5.10 show the analysis for the RECR-MAC protocol, and its other benchmark CR-MAC protocols.

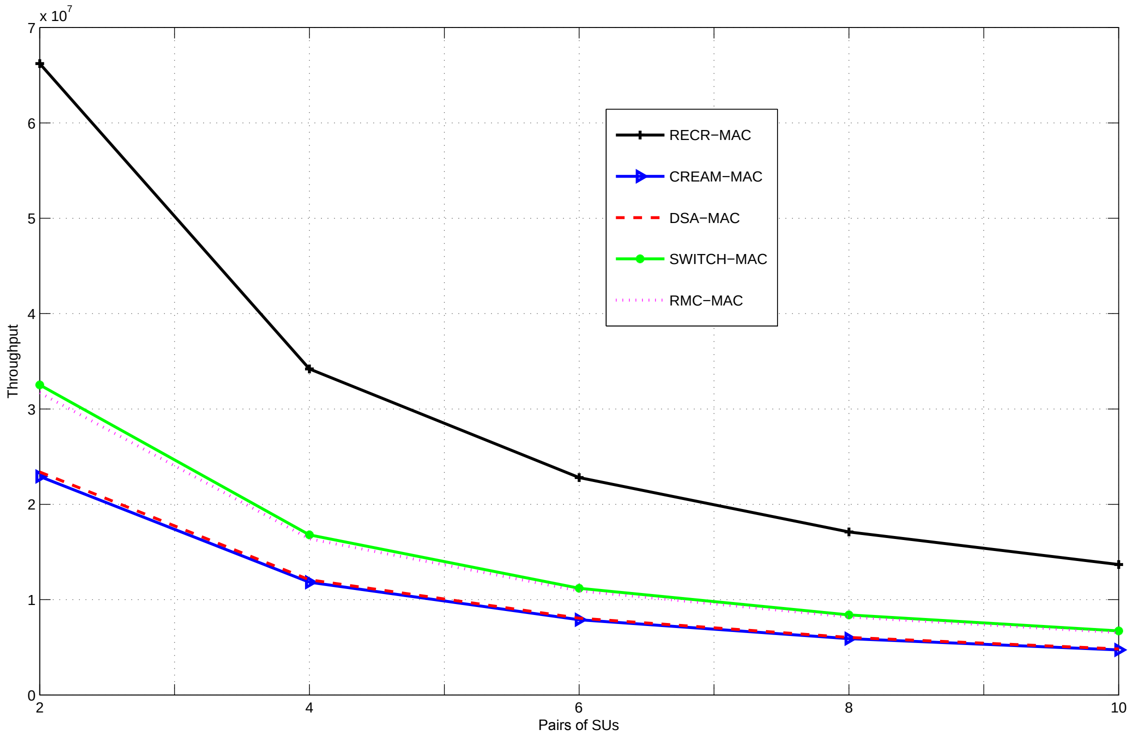

FIGURE 5.8: Throughput vs. Pairs of SUs for Data = 1000 Bytes (PU returns)

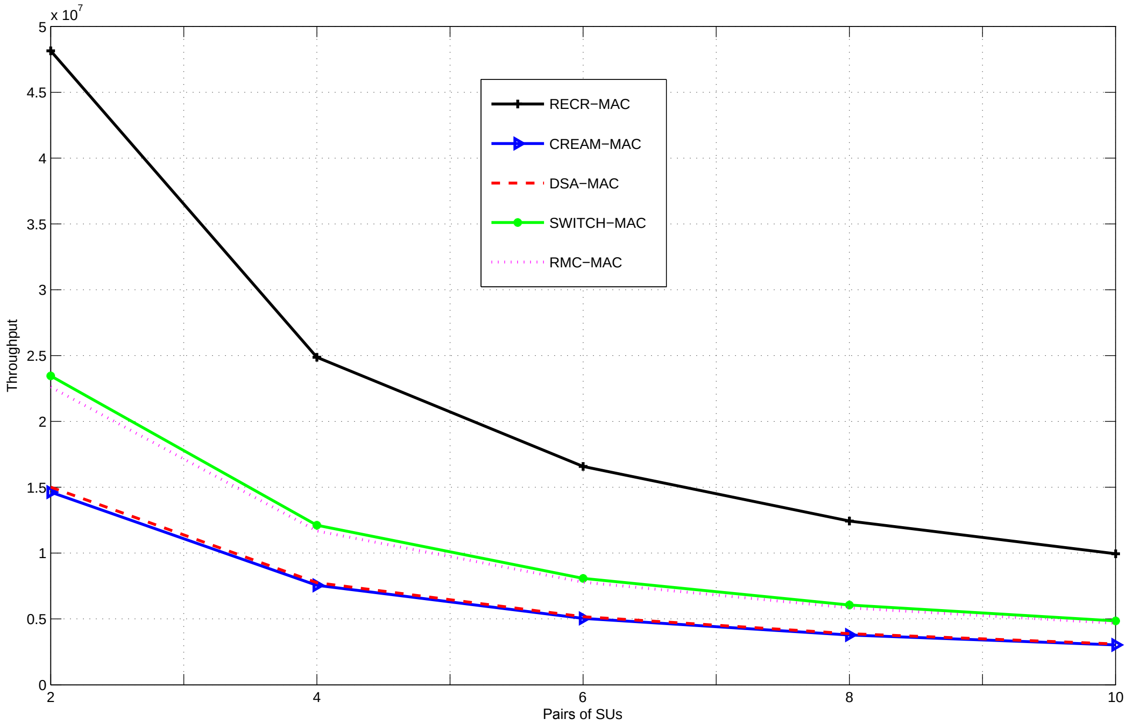

FIGURE 5.9: Throughput vs. Pairs of SUs for Data = 500 Bytes (PU returns)

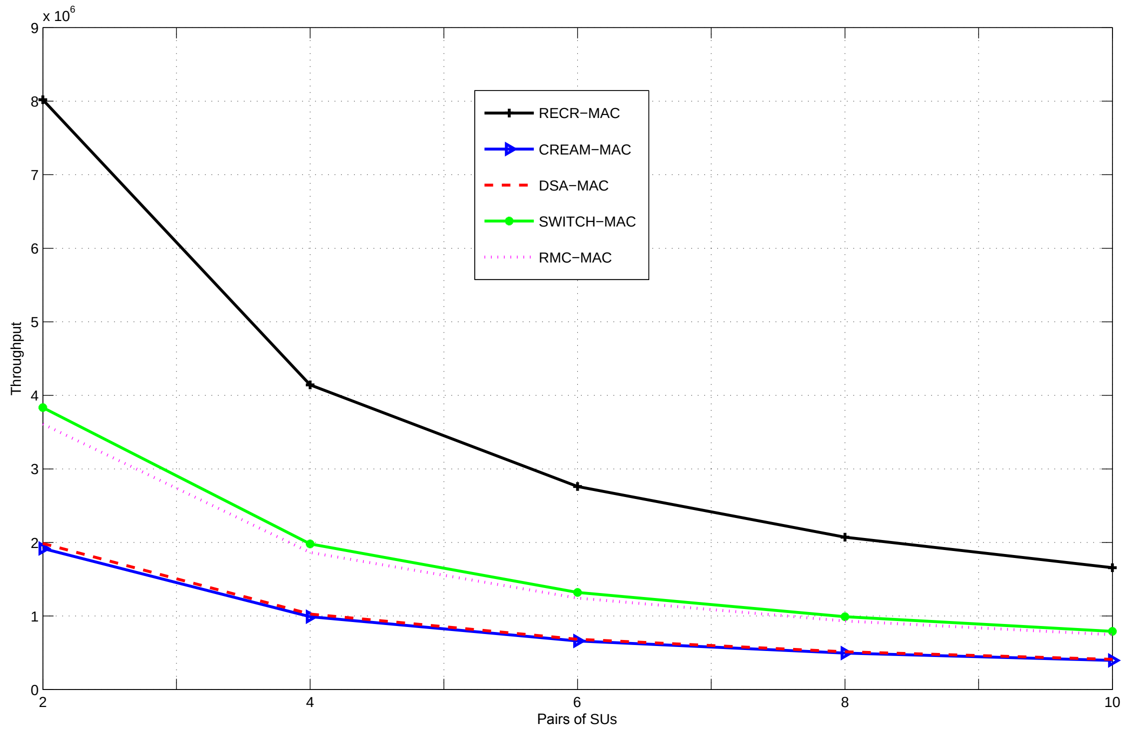

FIGURE 5.10: Throughput vs. Pairs of SUs for Data = 50 Bytes (PU returns)

Figures 5.8 to 5.10 demonstrate that the proposed RECR-MAC protocol has high throughput for different numbers of SUs. These results are expected based on the BDC technique adopted by the RECR-MAC protocol. Moreover, CREAM-MAC and DSA-MAC do not use BDCs: hence if PU returns during the data communication, both protocols re-start the entire process. SWITCH-MAC and RMC-MAC have adopted BDCs without consider the situations; if PU returns over the PDCs, both protocols switch to BDCs. If the BDCs are already occupied, then both CR-MAC protocols are obliged to re-start the entire process, similar to CREAM-MAC and DSA-MAC. However, the RECR-MAC protocol utilises two DCHs simultaneously, instead of a single DCH for communication and if PU returns on either of the DCHs, both DCHs act as a backup to each other and avoid the restarting process. This introduction of the BDC saves communication time, transmitting energy and increases throughput as depicted in Figures 5.8 to 5.10.

5.6 Summary and Contributions

As discussed in the previous chapters, the selection of reliable DCHs and the introduction of the BDC have reduced communication time among the SUs, which plays a vital role, directly impacting the performance of the CRAHNs in terms of energy consumption and throughput. This chapter therefore examined the other contributing features of the RECR-MAC protocol (e.g. transmitted energy and throughput).

The importance of the energy consumption for the RECR-MAC and benchmark CR-MAC protocols have been analysed through the consideration of multiple factors. The analytical analysis demonstrates that the average energy consumed by RECR-MAC protocol is lower in comparison to other benchmark CR-MAC protocols, with payloads of 1000 bytes, 500 bytes and 50 bytes respectively, without and with PU interference. Furthermore, an analytical model has been developed based on multiple factors to analyse the throughput of the RECR-MAC protocol with benchmark CR-MAC protocols without, and with, PU returns. Thus, the above results demonstrate that the RECR-MAC protocol has high throughput in comparison to the benchmark CR-MAC protocols. The next chapter discusses the behaviour of PUs activity and its impact over the RECR-MAC protocol.

Chapter 6

Behaviour of Primary Users Activity and its Impact over the RECR-MAC protocol

In this chapter, the impact of PU activity over the DCHs will be examined in detail under the ideal conditions with fixed number of SUs, PUs and available DCHs. In addition, the RECR-MAC and other CR-MAC protocols consider BDC and select random channels without considering the channel ranking to validate the performance of the RECR-MAC protocol and its comparison with other selected CR-MAC protocols. For example, if 2 DCHs are available, then only two SUs can contribute for the communication. Similarly, if 4 DCHs are available then only four SUs can contribute for communication, and so on. It may possible that the any selected CR-MAC protocol selects the DCH which takes less communication time to exchange its data frames as compared to the other CR-MAC protocol along with the RECR-MAC protocol. The detail of ideal conditions will be discussed in the following sections.

The effective progress in research and its development would not be possible without simulation. Simulation and modeling are considered to be the most significant method to understand, define, prove, visualize and compute for the network performance. In general, there are two types' of network modeling named as analytical modeling and computer based modeling. The analytical modeling has been based on mathematical equations and provides the network characteristics.

Furthermore, it covers only a one dimensional vision of the improved network and that is unable to provide the details of leaving and joining the nodes in the network. The computer based modeling and simulation are generally categorised as discrete event simulation and continuous time simulation. The analysis of the complex system essentially requires computer based simulation that is capable to compute the time that is correlated with the real life event and situation.

In this chapter, the MATLAB R2009b simulator [159] is used to investigate the performance of proposed RECR-MAC protocol and its comparison with other benchmark CR-MAC protocols. MATLAB simulation is based on high level programming language that supports numerical computation and visualization. MATLAB can create models and analyse data for a wide range of applications such as communication systems, including signal processing, control engineering and computational finance. In addition, MATLAB programming, functions and libraries are used to build CR model that investigate various spectrum sensing, prediction, communication and management techniques between primary and secondary users [160] [161].

It is a precondition for the SUs to first record the activity of the PUs before commencing their communication. The regulatory bodies (such as the FCC and OFCom), do not permit the SUs to interfere with licensed user traffic, irrespective of circumstances. Therefore, this chapter discusses the impact of PUs activity and communication time over DCHs, and BDC for the proposed RECR-MAC and benchmark CR-MAC protocols. The ON/OFF activity of the PU is not regular and may be highly influenced by the activity of the SU during communication in the CRAHNs. It is therefore important to record the precise activity of the PUs and select DCHs during the exchange of control information. Moreover, the issue becomes more complicated when the PU returns to its licensed channel and the SUs have no opportunity to switch to another DCH (named a BDC) to continue the communication instead of re-starting the entire procedure. To deal with the aforementioned issues, a Reliable and Energy Efficient Cognitive Radio Multi-Channel MAC Protocol for Adhoc Networks (RECR-MAC) protocol is proposed. This selects DCHs during the control information handshaking and switches to a BDC when PUs return to their licensed channels. In the RECR-MAC protocol, each SU is equipped with two transceivers with Software Defined Radio (SDR) capabilities that can dynamically utilise two licensed channels simultaneously, in order to exchange information among the SUs in the network. In addition, each SU has a sensor that can detect and capture the return of the PU, and neighbouring cognitive node activity, while both transceivers are busy transmitting and receiving data over the DCHs. The SUs of the RECR-MAC protocol utilises both DCHs for communication, where both selected DCHs provide backup for each other. With the help of two-way handshaking over the DCCH with two transceivers and a sensor, the RECR-MAC protocol can effectively handle the traditional hidden terminal and the multi-channel hidden terminal problems as described in Chapter 3.

The remainder of this chapter is organised as follows: Section 6.1 analyses in detail PU activity, including the four activity patterns. Section 6.2 describes the prediction of the availability of DCHs in the CRAHNs. Section 6.3 analyses the impact of the channel selection strategy over the BDC. Section 6.4 discusses the impact of primary radio activity for the selection of the DCHs, and the effect of different payloads over the communication time among the SUs with, and without, backup data channels. Moreover, the PU activity is modelled as an alternating ON and OFF, based on the Markov Renewal Process (MRP), as depicted in Figure 6.1 [94] [45] [116]. It is to be noted that the ON and OFF PU activity has recorded the time duration in which the channel can be utilised by SUs without causing any harmful interference to the PUs [62].

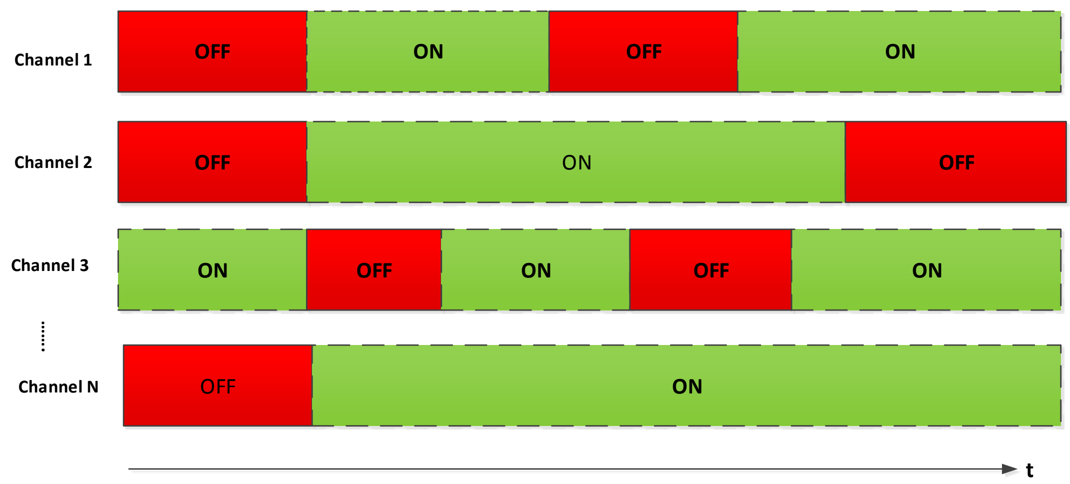

FIGURE 6.1: ON and OFF activity of the PUs in CRNs

6.1 Primary Users' Activity

As discussed in in Chapter 3, the activity of the PU (i.e. the presence and absence of the primary radio signal) can be represented as continuous time, alternating ON and OFF Markov Renewal Process (MRP). In MRP, the PUs' activity is modelled as an alternating ON and OFF, as depicted in Figure 6.1. This PU model has been widely used in the literature [162] [62] [163] [94] [164]

[45] [165] [116] and provides the spectrum ON/OFF pattern for the public and commercial safety usage [166]. The authors in [167] [168] have adopted a similar ON/OFF approach for data and voice communication. In addition, CREAM-MAC [23], ECR-MAC [24] and RMC-MAC [57] are well known protocols that also have adopted the same ON/OFF approach to record the activity of the PUs. The key objective of the ON/OFF PU activity model is to record the free time period in which the SUs can be utilised without causing interference to the PUs. The ON state is represented by the value of 1 and indicates that the licensed spectrum band is occupied by the PUs and is unavailable for the SUs. Similarly, the OFF state is represented by the value of 0, and indicates that the channel is unoccupied by the PUs and available for the SUs. There are two possible states can be obtained from the channel sensing to record the pattern of the PUs' activities over spectrum bands such as ON to OFF and OFF to ON. Figure 6.2 presents the channel model for the i-th licensed DCH, based on the alternating ON/OFF MRP for the activity of the PUs.

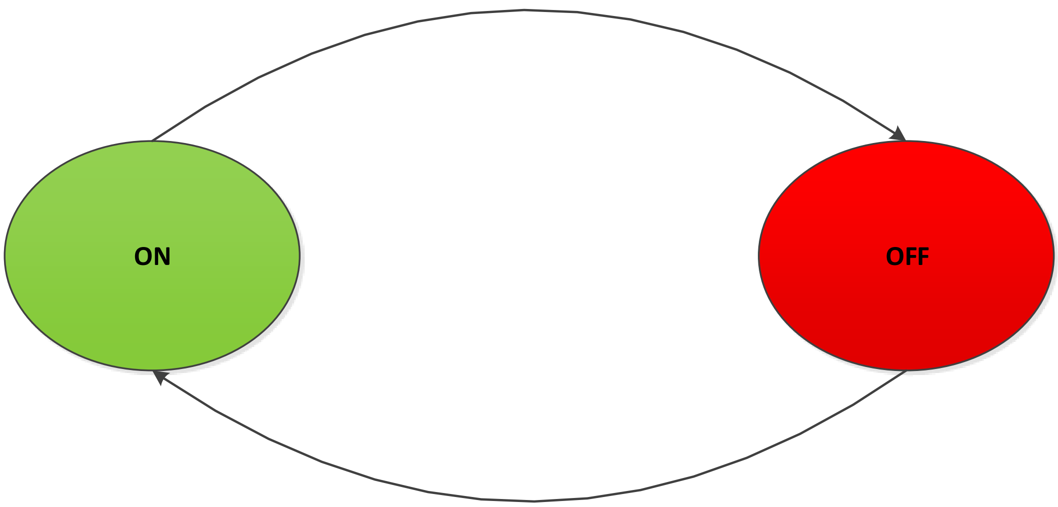

FIGURE 6.2: ON and OFF PUs activity/ channel model for the i-th licensed data channel

The time duration of ON/OFF states of licensed DCH is represented by T^i_{ON} and T^i_{OFF}, respectively, based on the PUs' activity. The time duration of the ON/OFF states are assumed to have an Independently and Identically Distribution (i.i.d) [23]. Each arrival of the PUs is independent and each transition follows the Poisson arrival process, where the time duration of ON/OFF periods are distributed independently [169] [57] [24] [94] [23]. There are four types of PU activity patterns as discussed in [170] [171] that can be considered for the CRNs. The following comprise the activities of the PUs:

Extensive PU Activity: In extensive PU activity, the channel has long ON and OFF times. This type of activity is observed by mobile phone companies as licensed users. These companies can offer night-time unlimited packages.

High PU Activity: In this activity, the channel has a short OFF and long ON time. This type of activity can be easily found in city/town centres, particularly at peak time in central London.

Low PU Activity: This type of activity is beneficial for the CRNs where the channel has a long OFF time and short ON time for the licensed users. This type of activity can be observed in remote and rural areas.

Intermediate PU Activity: In this type of activity, the channel has a short OFF and ON time. This type of activity can be observed at airports, public transport and railway stations.

The probability of the PU over the DCH being in the ON state at time t can be denoted as $P_{ON}(t)$. Similarly, the probability of the PU over the DCH being in the OFF state at time t can be denoted as $P_{OFF}(t)$.

$$P_{ON}(t) \quad + \quad P_{OFF}(t) = \quad 1 \tag{6.1}$$

The probabilities of $P_{ON}(t)$ and $P_{OFF}(t)$ are also discussed in [57] [24] [62] [94] [23] and represented in Equation 6.1. Based on the four types of PUs activity patterns and Equation 6.1, the proposed RECR-MAC protocol is most suitable for low PU activity cases, where the SUs can utilise high $P_{OFF}(t)$ for communication.

6.2 Prediction of the Availability of Data Channels under the PUs Activity

As already discussed in the above chapters, channel sensing is performed by the physical layer, which updates its information to the layer above, such as the MAC layer for the execution of the spectrum sensing strategy. The MAC layer sensing scheduler is able to determine the PU's transmission times and sensing detail. Therefore, the physical layer is responsible for providing the list of the channels and their free time to the MAC layer for the SU's communication [133]. In addition, the physical layer is responsible for updating PU return information to the MAC layer, which avoids interference among the secondary and primary users. In order to validate the received information from physical layer to MAC layer at the optimal detection threshold point, the value of the Probability of the False Alarm (P_{FA}) should be minimised. The optimal detection threshold point is achieved if the value of the probability of false alarm is minimised and lies between 0.01 to 0.1 [34] [172]. The optimal detection threshold is the point at which the SUs decide their transmitting policies for communicating over the DCHs without interference to the PUs.

To achieve the optimal detection threshold point, three popular approaches have been demonstrated to identify the signal energy, as discussed in Chapter 3: i) matched filter detection; ii) energy detection; and iii) cyclostationary feature detections [127] [92] [31] [94]. Matched filter is the optimal detection technique which requires prior knowledge of the PUs, but it has low computational cost. Cyclostationary detection requires partial knowledge of the PUs with high computational cost. Energy detection requires a short sensing time and low complexity. Additionally, it does not require prior information of the PUs [93] [128].

One aim of this thesis is to obtain reliable DCHs for successful communication among the SUs. However, there might be the case where the SU believes that the channel is available when, in fact, it is not. In addition, it can be possible that the channel is not available, but mistakenly the SU attempts to utilise the channel, which can cause harmful interference to the PUs. Therefore, it is important to consider the appropriate sensing technique which avoids sensing error and minimise the interference among PUs and SUs. When selecting a sensing method, a number of tradeoffs should be considered with respect to the hardware and SU requirements, including long or short sensing time and whether prior knowledge of PU is required or not, etc. There are two types of probabilities for sensing the spectrum bands by using the energy detection technique [129] [64]. The first type occurs when the channel is unoccupied but the sensor of the SU can decide when the channel is occupied. This situation is called P_{FA} and is denoted with (H_0). The second type occurs when the channel is occupied, but the sensor of the SU can decide when the channel is available. This is called Probability of Misdetection (P_{MD}) and denoted with (H_1). The increase value of the P_{FA} and P_{MD} decrease the spectrum access opportunities for SUs.

The energy detector technique requires the longest detection time, if the value of the Signal to Noise Ratio (SNR) stays in between -10 dB and -40 dB [173]. The authors in [174] have proposed that the detection performance can be improved by varying the value of the P_{FA} from 0 to 1. Similar approaches have been adopted by authors in [153] [175] [176] to obtain the value of the P_{FA}. According to the IEEE 802.22 Workgroup in [177], the P_{FA} can vary from 0 to 1, but if the value of the P_{FA} remains between 0.01 (1%) and 0.1 (10%), then the energy detector can obtain the correct information concerning the sensed channel(s). This has the potential to increase the opportunity for the SUs to communicate successfully over the DCHs and increase the throughput of the CRNs. Based on the references in [177] [153] [175] [178] [176], in this thesis the optimal value of P_{FA} to be considered is set as 0.1 to receive reliable information of the available channels for communication among the SUs. To conclude the discussion, the reduced value of the false alarm provides reliable information to the link layer and increases network throughput.

During the initialisation process of the CRAHN, the SUs receiver determines the activity of the PUs, including the list of the available channels and their free time by using the energy detection technique. However, its detection capability does not work during communication among the SUs. Therefore, the cyclostationary feature detection technique is assumed to detect the return of the PU during the communication, using the sensor of each SU. To summarise: the key objective of spectrum sensing is to achieve the optimal detection threshold with the minimum value of the P_{FA}. This provides the maximum opportunity to the SUs to access the spectrum and improves network reliability by selecting unoccupied channel(s).

6.3 Impact of PU Activity over the Backup Data Channel

The continuation of the SUs' communication over the DCHs is a challenging task when PU returns during the communication. When two SUs commence their communication over the DCHs, and the sender node is unable to receive the ACK frame from the receiver node, then an unsuccessful communication is implied. In the literature review, the majority of the researchers are of the opinion that the reason for not receiving the successful ACK may be caused by the return of the PUs, poor channel quality, misdetection and fading, etc. In the RECR-MAC protocol, the reliability of the DCH is increased if the sending SU receives a positive ACK from the receiving SU. Similarly, if the sender SU does not receive the ACK (negative ACK) from the receiving SU, this indicates interference over the channel and decreases the probability of the successful communication. If PU returns during the communication among the SUs, the RECR-MAC protocol is able to manage the situation and the affected traffic of the PDC switches to the BDC, to continue the communication without interruption.

As discussed in the literature review, the majority of the CR-MAC protocols have not considered and reserved the BDC and prefer to not occupy the additional channel. On the contrary, if PUs return over the DCH during the data communication, then the CR-MAC protocols need to re-start the whole process due to the absence of the BDC. However, some of the protocols (such as SWITCH-MAC, RMC-MAC) have adopted the BDC, but are unable to validate the occupancy of PU activity over the BDC. For example, if the PU returns to the BDC and then over the PDC followed by the SUs switching to the BDC to find the channel already occupied. In such situation, the CR-MAC protocols are required to re-start the entire procedure. In order to overcome such problems, the RECR-MAC protocol introduces a novel approach, where the SUs select DCHs and introduces the BDC, leading to simultaneous communication over the PDC and BDC. If PU returns on either of the PDC then the SUs switch to other PDC. Thus, the PDCs act as BDC for each other. Following Section shows the importance of the BDC under the impact of PUs activity over the DCHs during the communication.

6.4 Performance Evaluation

This section describes the performance evaluation of the primary and backup data channels selection strategies under different primary radio activities without considering the channel ranking. To attain this, a number of simulations will be described in the following subsections: i) without PU returns; and ii) PU returns with medium and high frequency over the DCHs, as shown in Figures 6.3 - 6.11, using the Matlab Simulator [159]. Moreover, this section presents the affect of multiple payload sizes over the communication time among the SUs with, and without, BDC. The RECR-MAC protocol compares its characteristics and performance with other well known CR-MAC protocols (such as the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols), which are used as benchmark protocols.

6.4.1 Impact of the Primary Users Activity over the DCHs

There are four CR-MAC protocols involved as benchmarks in this simulation, due to their similar characteristics for the comparison with the proposed RECR-MAC protocol as discussed in Chapter 4. It may possible that any selected CR-MAC protocol performs better during any simulation run as compared the other selected CR-MAC protocols and the RECR-MAC protocol due to the lack of channel ranking. However, the overall performance of the RECR-MAC protocol could be better as compared to other selected CR-MAC protocols based on the designed framework of the BDC, as discussed in Chapter 3.

The proposed RECR-MAC protocol is able to manage any number of simulation runs and multiple sizes of the data frames during each Scenario, in order to validate the performance of the proposed protocol and its comparison with other benchmark CR-MAC protocols. In this subsection, each simulation runs 10 times for each Scenario. The SUs record the following statistics during each run of the simulation: a) how much data it can transmit for the RECR-MAC and the benchmark CR-MAC protocols; b) how much time is required for the SUs to exchange information over control and data channels; and c) data per second, throughput, among the SUs. Moreover, a DCCH is assigned for exchanging control information, and twenty DCHs are allocated for data communication. Data size starts from 1000 bytes to 50 bytes for the correspondence DCHs 1, to 20 with the decrement of 50 bytes. The available free time duration for the DCH 1 is 2100 μs, DCH 2 is 2050 μs and decreases with the rate of 50 μs for the following DCH 20 is having 1100 μs, as shown in Figures 6.3 and 6.4.

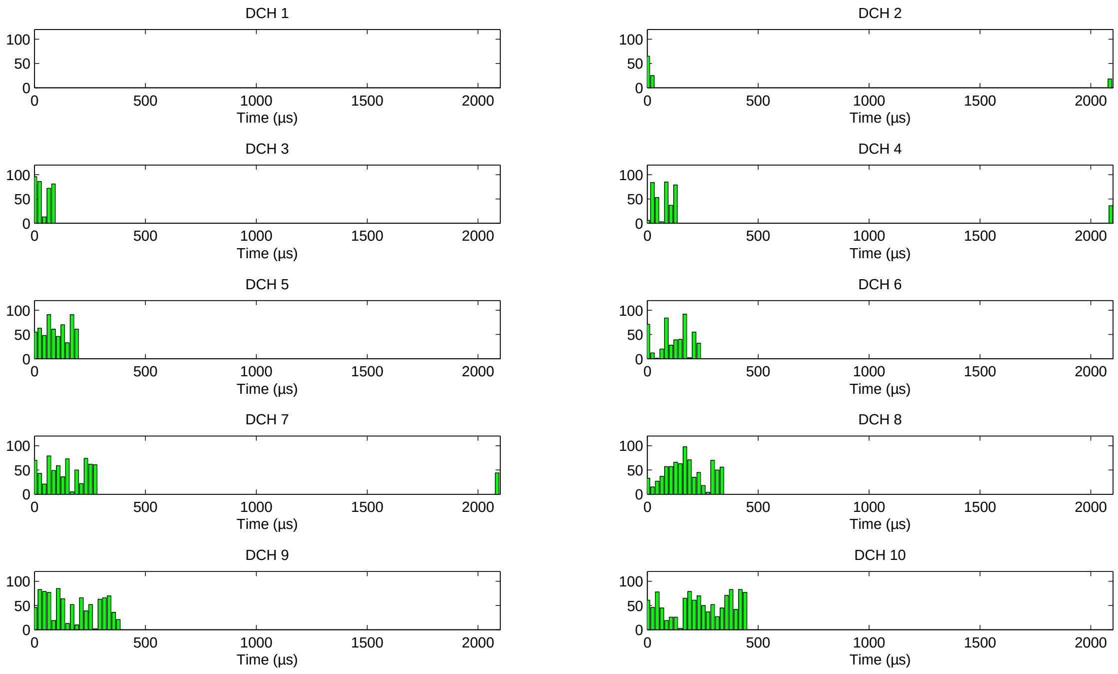

FIGURE 6.3: PUs Activity over DCHs 1 to 10

The green lines demonstrate the PU activity of the DCHs, and the white space shows the free time for the SUs' communication.

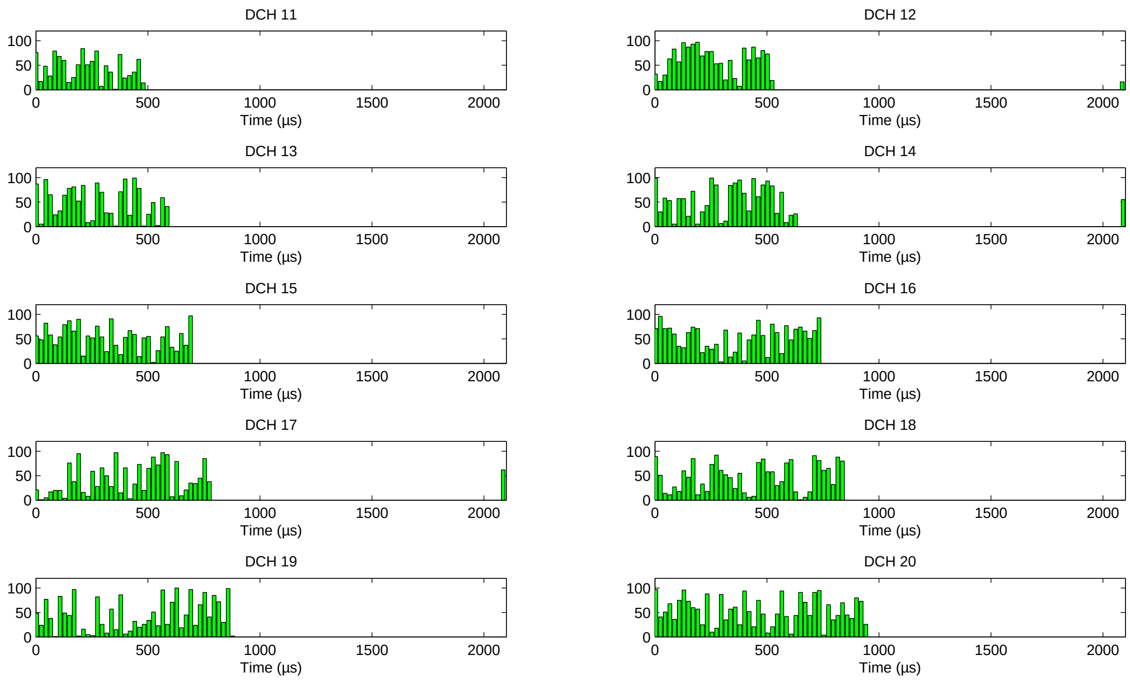

FIGURE 6.4: PUs Activity over DCHs 11 to 20

6.4.1.1 Scenario 1: Medium PU activity over the Data Channels

In this Scenario, the PU returns at 5th and 8th intervals during this Scenario for each protocol, as shown in Figures 6.5 to 6.7, where each protocol either switches to BDC channel or re-starts its entire process based on its characteristics. For example, CREAM-MAC requires the re-start of the entire process, as this protocol does not maintain the BDC during the selection of the DCHs. DSA-MAC selects the best DCH based on the SINR, without considering the BDC as well. SWITCH and RMC-MAC switch to BDCs without considering the appropriate selection criteria of the DCHs. However, RECR-MAC uses two PDCs, and if PU returns to any PDC, then the other PDC acts as a BDC to successfully accomplish the ongoing communication. In Figure 6.5, the x-axis demonstrates the number of SU runs. For example: during the first run, only two SUs can transmit data; during the second run, 4 SUs are able to participate and transmit the data. This increases respectively until reaching 10 runs with 20 SUs (10 pairs). The y-axis indicates the successful data transmission among SUs for each run. The RECR-MAC and SWITCH-MAC protocols are able to transmit greater amounts of data among the SUs at each run, as compared to the CREAM-MAC, DSA-MAC and RMC-MAC protocols, based on the characteristics shown in Figure 6.5.

It may be possible that any CR-MAC protocol may select the best channel based on its DCH selection criteria and its require less time to transmit same amount of data during any simulation run, when compared to other CR-MAC protocols. However, based on the random channel selection criteria, the CR-MAC protocol may select the worst channel instead of the reliable channel, and so be unable to transmit the information during the free time acquired by the unavailability of the PU, or require multiple attempts to transmit such information.

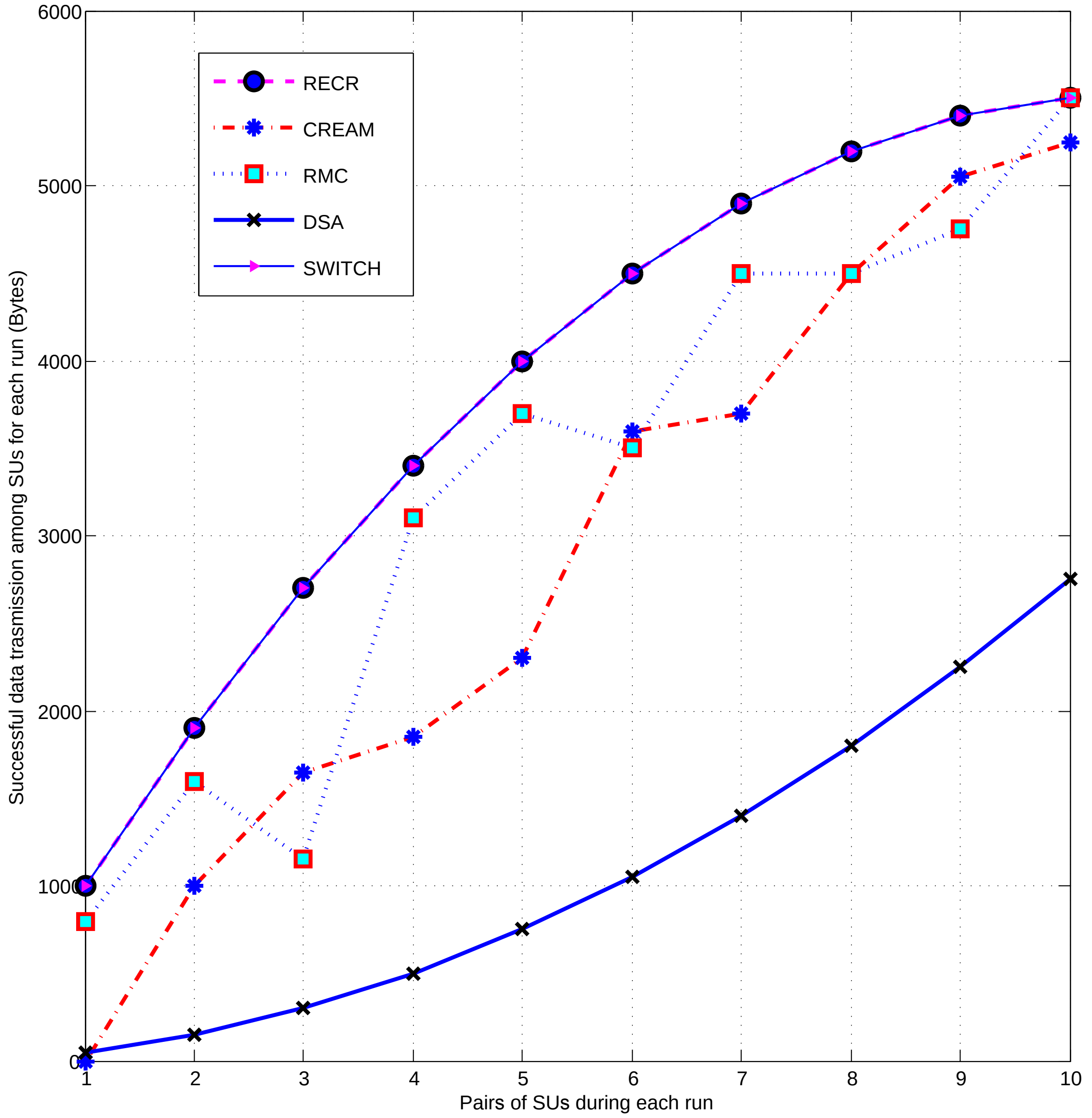

FIGURE 6.5: Successful data transmission among pairs of SUs for each run

The abrupt rise of the curves for the CREAM-MAC and DSA-MAC protocols demonstrate the shortcoming of the BDC in these protocols, and re-starts the entire communication process. This requires additional time to exchange the control and data information among the SUs. Figure 6.6 shows the PU returns during communication at the 5th and 8th runs of the simulation during this Scenario. As discussed above, the DSA-MAC protocol may utilise less communication time during the initial simulation runs as compared to the RECR-MAC protocol. Moreover, the following figure clearly indicates that the CREAM-MAC and DSA-MAC consume more time over control and data channels to transmit the data and RECR-MAC utilises less communication time to transmit the same amount of data when compared to the other CR-MAC protocols in this simulation.

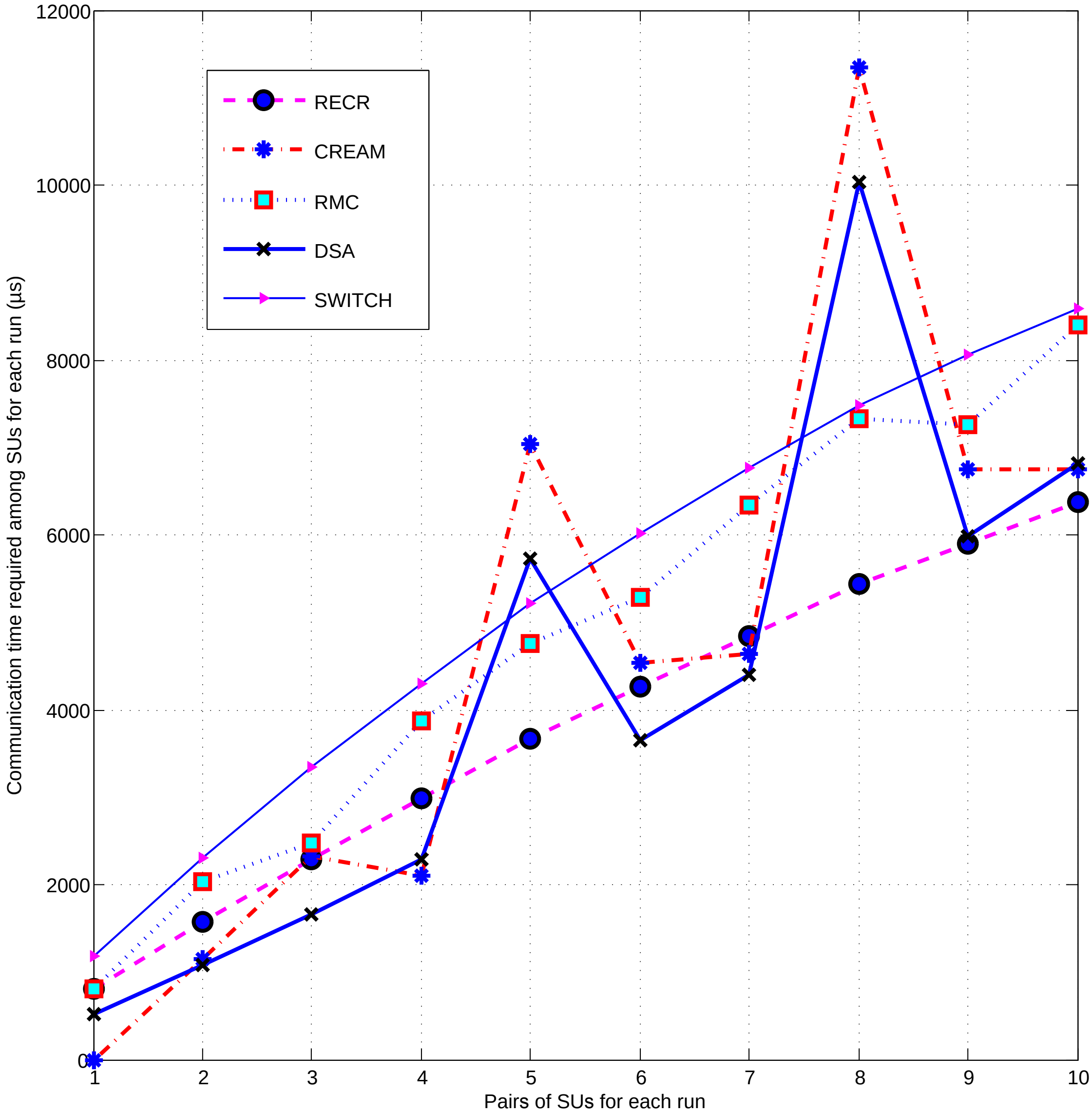

Figure 6.6: Time required for each CR-MAC for the transmission of data among SUs

Figure 6.7 indicates that the RECR-MAC protocol has the highest throughput in comparison to other CR-MAC protocols, due to the BDC strategy. It is also observed that the CR-MAC protocols which adopt BDCs have a smooth transition of the control and data frames. As an alternative, the CREAM-MAC and DSA-MAC protocols have an abrupt curve during 5th and 8th simulation runs due to the absence of BDC, which may decrease the quality of the protocol. On the other hand, the throughput of the RECR-MAC protocol is slightly reduced, due to fact that the number of SUs increased with the constant number of DCHs. In the following chapters, the researcher will perform the simulation with variable DCHs along with other dynamic parameters in order to further validate the performance of the RECR-MAC protocol and its comparison with other selected CR-MAC protocols.

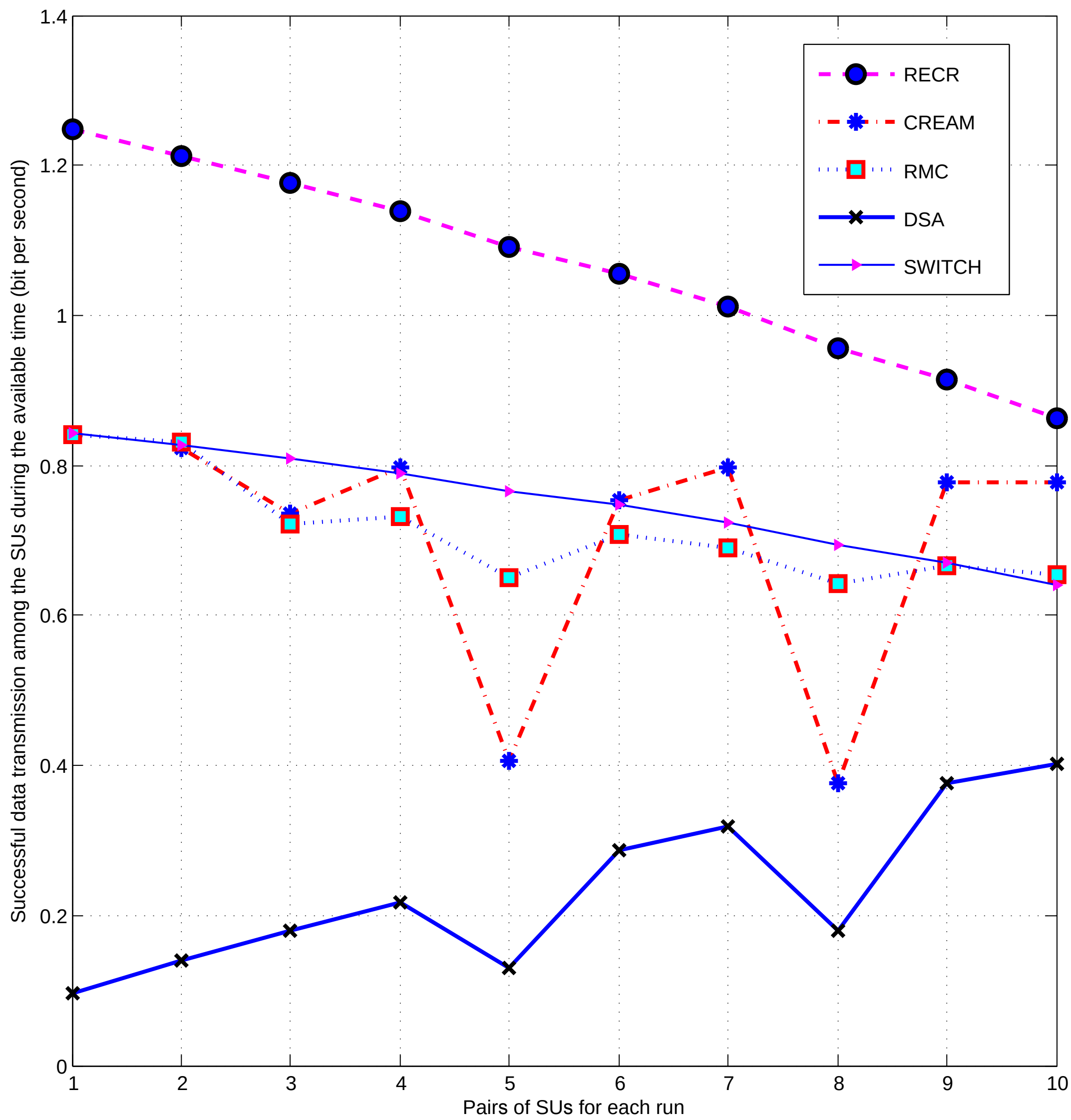

FIGURE 6.7: Throughput of each CR-MAC protocol

6.4.1.2 Scenario 2: High PU activity over the Data Channels

In this Scenario, the proposed RECR-MAC and benchmark CR-MAC protocols are using the same parameters as discussed in Scenario 1. However, in this Scenario, PU returns more frequently over the DCH in comparison to Scenario 1, as shown in Figure 6.8. This acts to validate the reliability and efficiency of the RECR-MAC protocol with the other benchmark CR-MAC protocols in the worst case scenario.

FIGURE 6.8: High PUs activity over the DCHs

Figure 6.9 reveals that the RECR-MAC and SWITCH-MAC protocols transmit high volumes of data when compared to the CREAM-MAC, DSA-MAC and RMC-MAC protocols, although the PUs return at the 3rd, 5th, 7th and 9th intervals during the data communication. The RECR-MAC protocol exchanges optimised frames over the DCCH and selects DCHs to transmit slightly higher data in comparison to the SWITCH-MAC protocol.

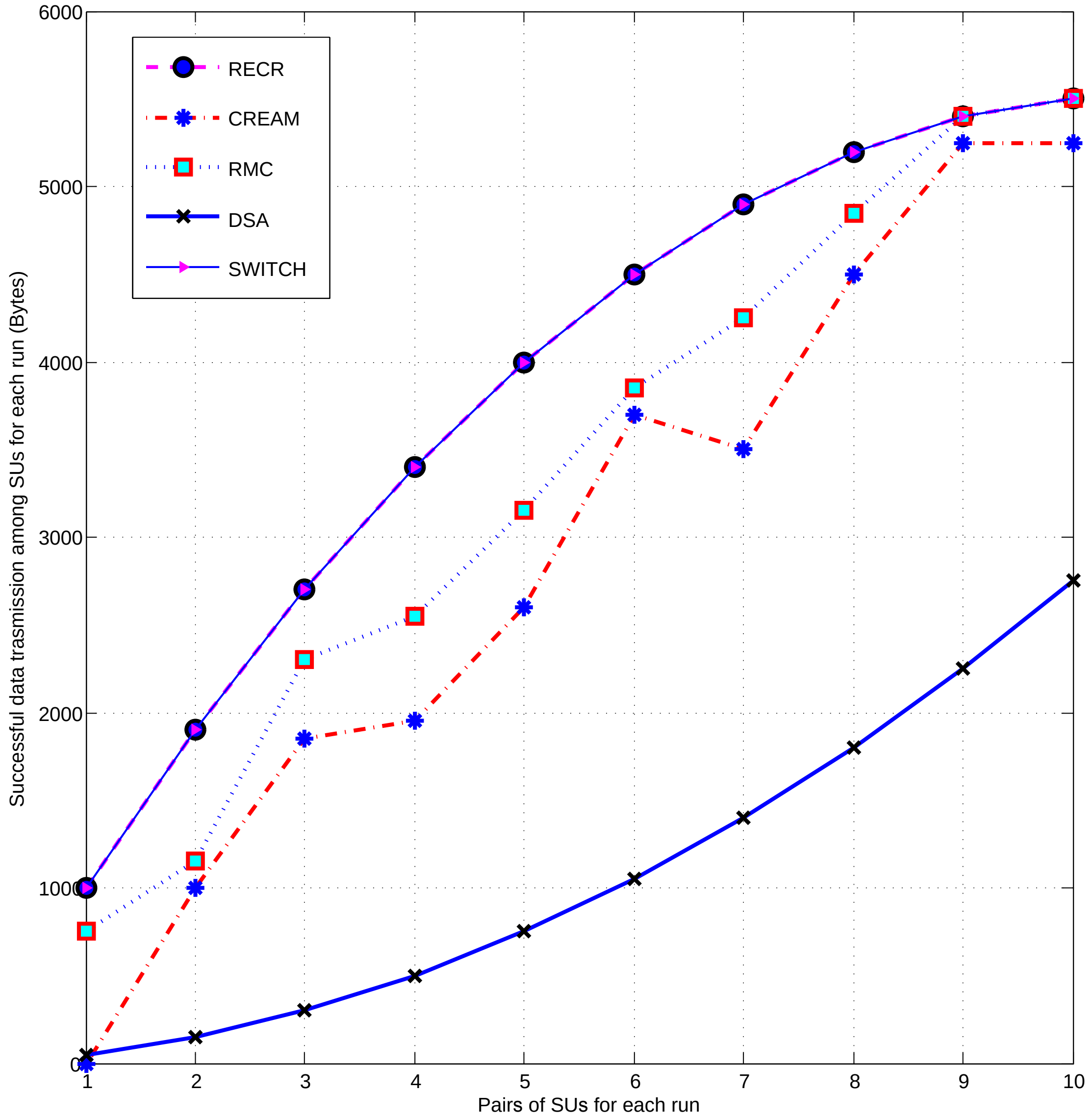

Figure 6.9: Successful data transmission among pairs of SUs during each run

Figure 6.10 illustrates that the RECR-MAC protocol consumes less communication time on each run in transmitting the data among the SUs when compared to other benchmark CR-MAC protocols. CREAM-MAC and DSA-MAC do not have BDC during the 3rd, 5th, 7th and 9th intervals to re-start the entire process for the communication. The abrupt rise curves for the CREAM-MAC and DSA-MAC protocols show the shortcoming of the BDC in these protocols and re-starts the entire communication process, which requires additional time to exchange control and data between the SUs. Thus, the RECR-MAC protocol requires less time to transmit the data over the DCH, even though the PU returns four times instead of two during the communication. On the contrary, the additional benchmark CR-MAC protocols require more time to transmit the same amount of data, due to high PU returns during the communication over the DCH.

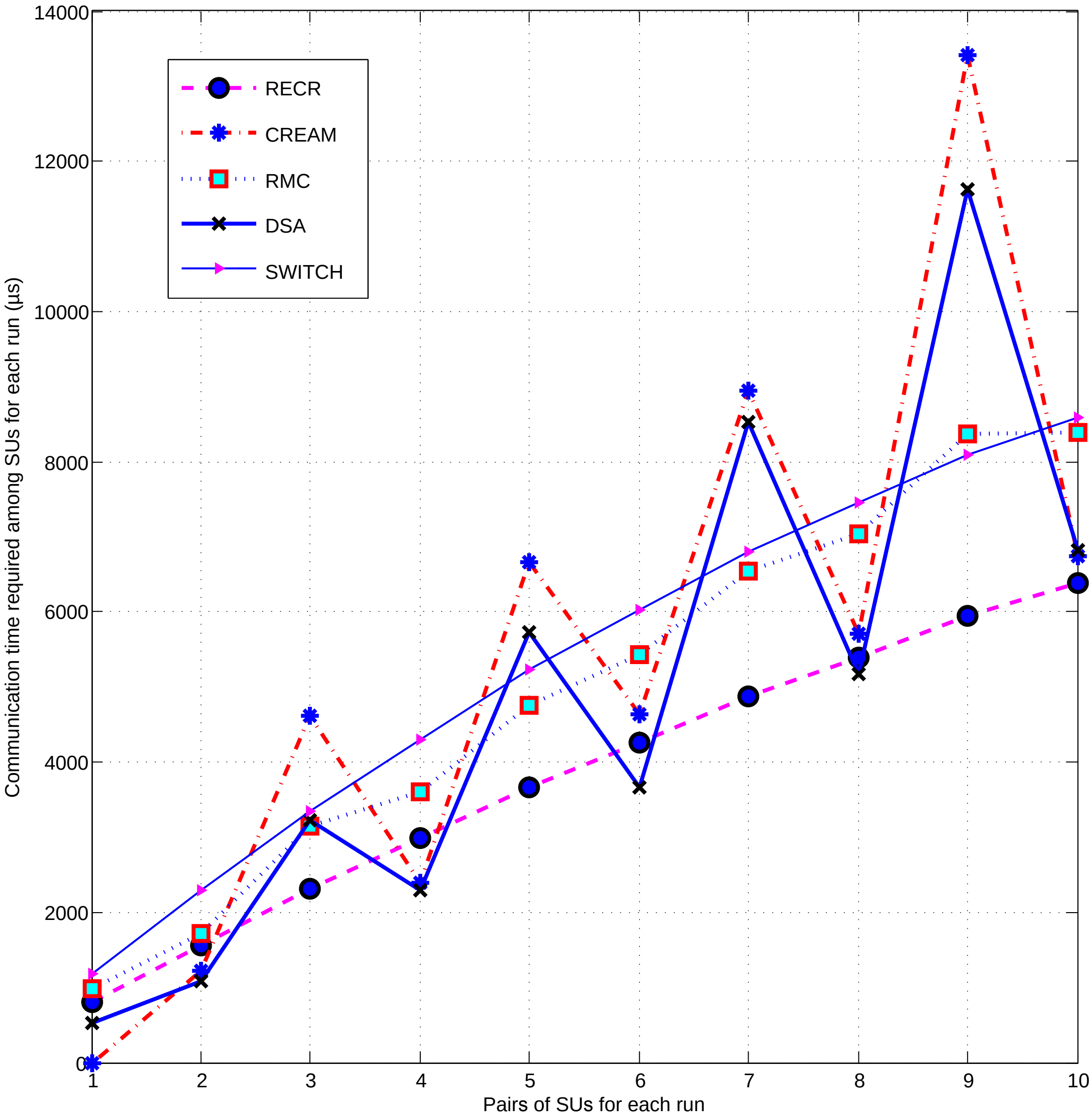

FIGURE 6.10: Time required for each CR-MAC for the transmission of data among SUs

Figure 6.11 demonstrates that the RECR-MAC protocol has high throughput when compared to the other benchmark CR-MAC protocols in order to demonstrate the validity and operation of the proposed protocol. The other CR-MAC protocols have less data rate based on their selected and designed parameters. The abrupt rise curves for the CREAM-MAC and DSA-MAC protocols demonstrate the shortcoming of the BDC, which require additional time to exchange the control and data information among the SUs. Therefore, in this Scenario, the PU's ON activity is higher than in the previous Scenario, but the network throughput of the proposed RECR-MAC protocol is slightly affected, due to the increase of SUs. Thus, the overall throughput of the RECR-MAC protocol is higher than other selected CR-MAC protocols as shown in Scenarios 1 and 2.

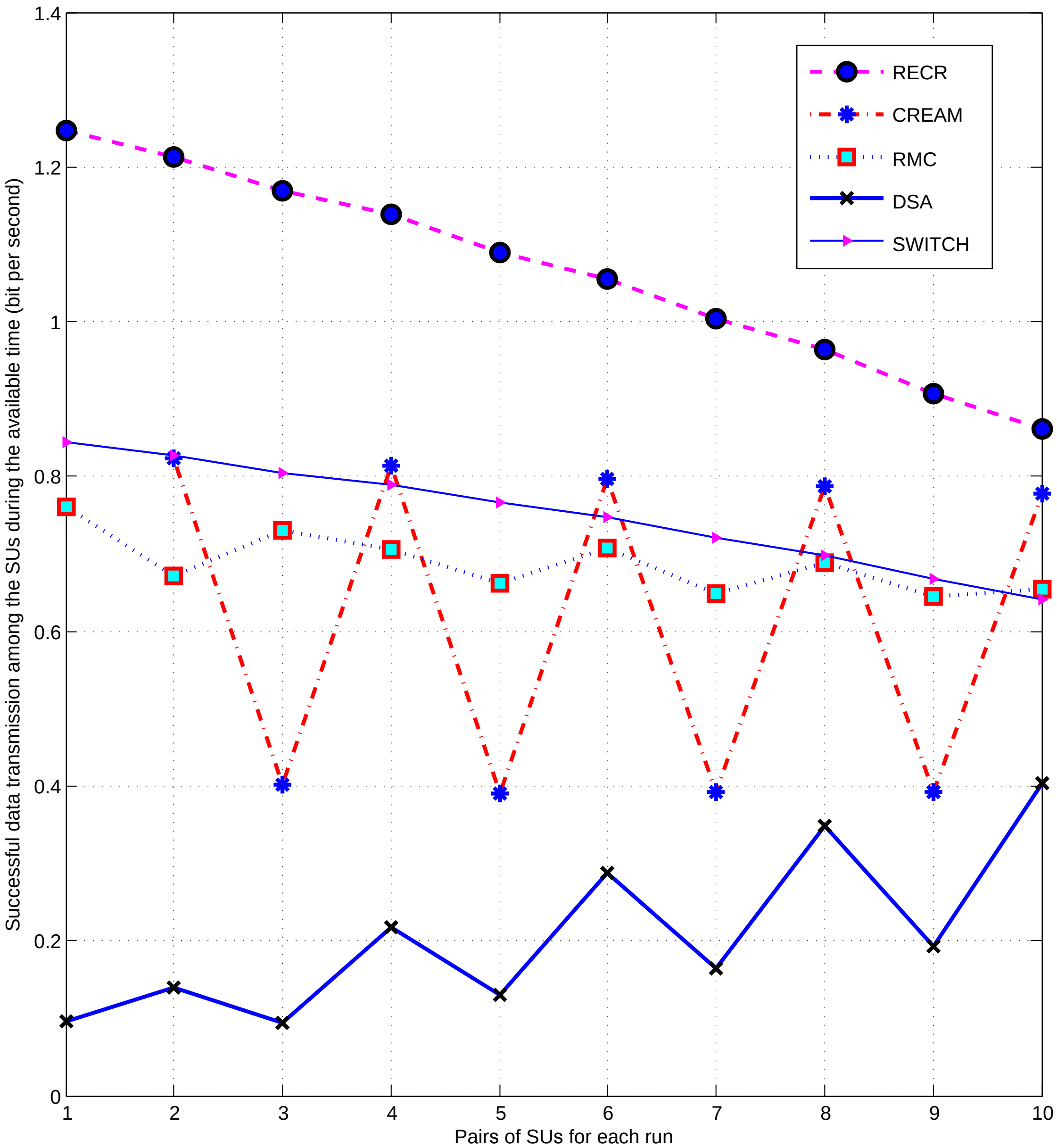

FIGURE 6.11: Throughput of each CR-MAC protocol

6.4.1.3 Scenario 3: No PU activity over the Data Channels

In this Scenario, the same parameters are used as adopted in Scenarios 1 and 2, but there is no record of a PU returning over the DCH. However, the abrupt curves of the CREAM-MAC protocol shows the shortcoming of the channel selection criteria when there is no PU returns during the communication. In this ideal situation, the RECR-MAC protocol is also compared in this thesis to the benchmark CR-MAC protocols for the validation of the proposed BDC. Thus, the RECR-MAC protocol is able to transmit high data in comparison to the other CR-MAC protocols, as shown in Figure 6.12.

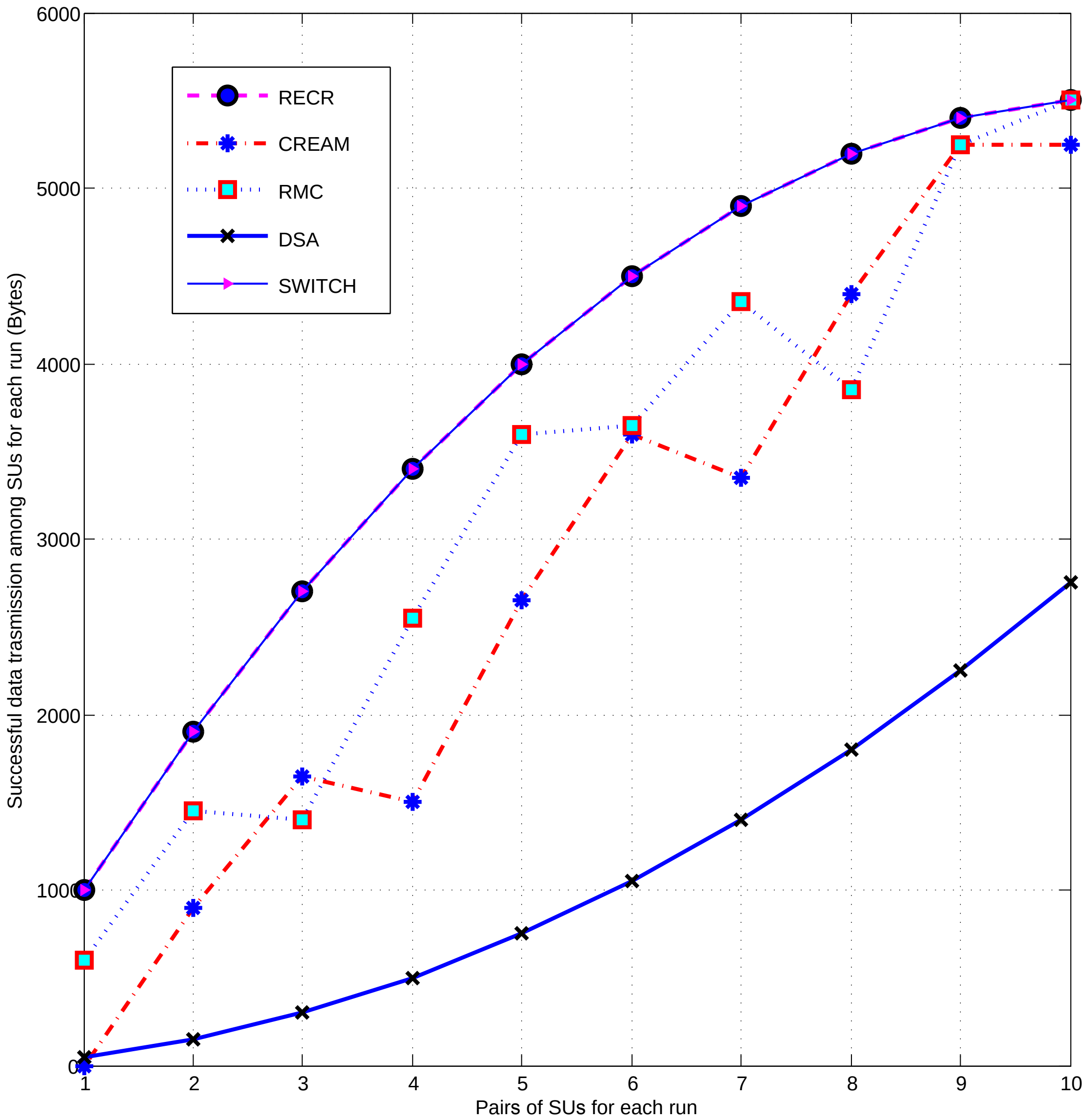

Figure 6.12: Successful data transmission among pair of SU for each run

Figure 6.13 illustrates the fact that the RECR-MAC protocol requires less communication time in comparison to other benchmark CR-MAC protocols. In this ideal case, the SWITCH-MAC protocol transmits higher data during initial simulation runs as compared to other CR-MAC protocols. However, the following figure show that the RECR-MAC protocol requires less communication time as compared to other CR-MAC protocols based on its proposed framework.

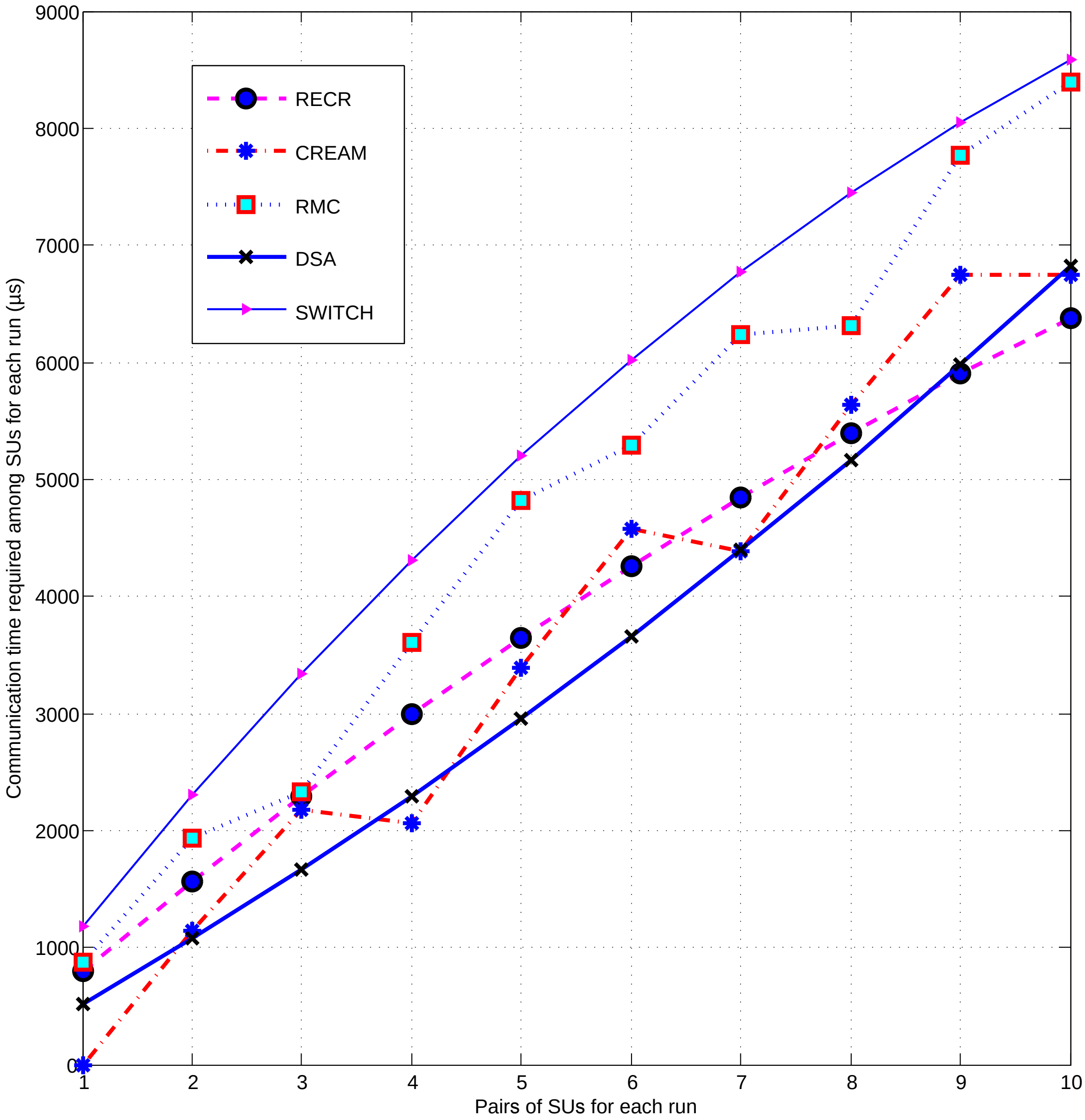

FIGURE 6.13: Time required for the transmission of data for each pair of SU

Moreover, the RECR-MAC protocol has high throughput in comparison to other benchmark CR-MAC protocols (as shown in Figure 6.14), even though there are no PU returns during the communication over the DCH among the SUs based on the BDC selection technique.

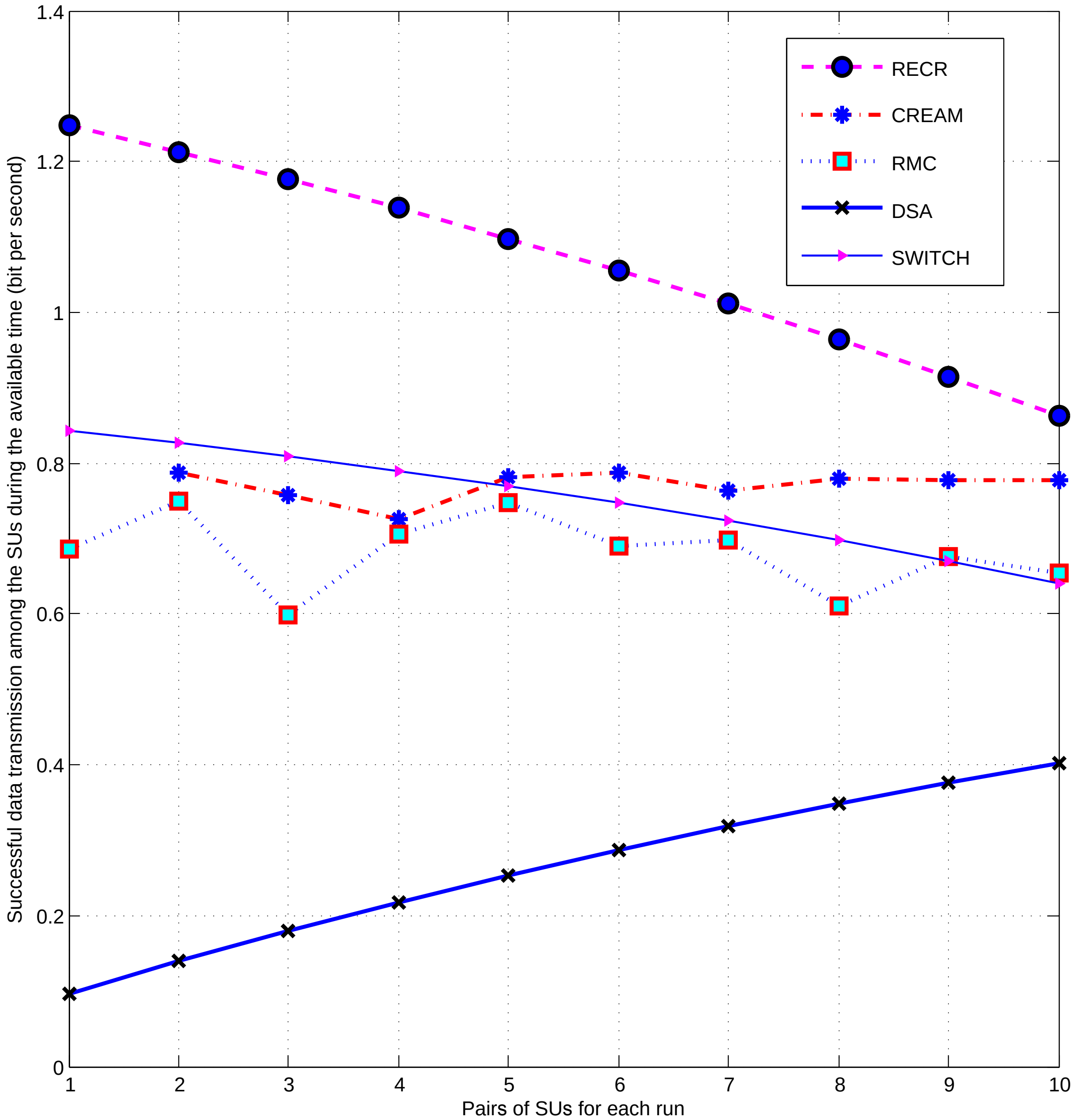

FIGURE 6.14: Throughput of each CR-MAC protocol

To conclude, the RECR-MAC protocol demonstrates the importance of the PU activity and its impact over the communication for the same amount of data to be transmitted among the SUs when compared with other CR-MAC protocols. In addition, BDC plays a vital role to improve the reliability of the RECR-MAC protocol, when compared with the other selected protocols used for comparison. The RECR-MAC protocol demonstrates that adopted channel selection criteria reduce communication time and increases network throughput. Moreover, BDC re-establishes the link among the SUs when PU returns during the communication period, which further improves the reliability of the network, reduces communication time and increases the overall data rate in the CRAHN.

6.5 Summary and Contributions

This chapter presented a discussion of the impact of PU activity recorded by the SUs and utilised the unoccupied time effectively with constant number of PUs, SUs and available channels. Under multiple patterns of the PU activity, there has been a calculation, followed by a comparison of the communication time required of the RECR-MAC protocol with other benchmark CR-MAC protocols with, and without, a BDC. The selection technique of the DCH and BDC proves that RECR-MAC requires less communication time to exchange data frames among the SUs. The researcher has adopted multiple sizes of payload in order to validate the effectiveness of the RECR-MAC protocol. Thus, Figures 6.5 to 6.14 demonstrate that the proposed protocol consumes the least amount of time over the DCCH. This allows the SUs to transmit increased data in comparison to the other CR-MAC protocols that use additional time over the DCCH, due to the additional handshaking for the selection of the DCH, and leave less time for communication over the DCH. Finally, the proposed RECR-MAC protocol exchange higher data among the SUs over the DCHs as compared the other selected CR-MAC protocols due to the selection criteria of its BDC. The next chapter presents the extensive simulation of the proposed RECR-MAC protocol and its comparison with benchmark protocols under the dynamic conditions where the contributing factors such as PUs, SUs, data size, available DCHs and PU returns do not depend on each other.

Chapter 7

RECR-MAC and CR-MAC Protocols: Performance Evaluation, Simulations and Comparisons

As discussed in the previous chapter, the effective progress in research and its development would not be possible without simulation. In this chapter, the MATLAB R2009b simulator [159] is also used to investigate the performance of the proposed RECR-MAC protocol and its comparison with other benchmark CR-MAC protocols. This chapter presents the extensive simulation of the proposed RECR-MAC protocol and its comparison with benchmark CR-MAC protocols under the dynamic conditions where the contributing factors such as PUs, SUs, data size, available DCHs and PU returns do not depend on each other. In addition, the impact of the channel selection criteria and BDC are considered simultaneously for the performance analysis of the proposed RECR-MAC and benchmark CR-MAC protocols.

During the initialisation of the network, the reliable channels are selected based on the maximum free time on the DCH, which is the OFF time of the PUs. The channel ranking thus depends on the number of positive or negative acknowledgments and the usage history of the DCHs. If more than two DCHs have the same value during the second, third and following iterations, then the DCHs are selected based on the maximum free time resulting from the activity of the PUs. The priorities of the DCHs are assigned based on RDCH 1, RDCH 2, RDCH 3, and RDCH 4, respectively (where RDCH 1 and RDCH 2 have the highest priority, RDCH 3 and RDCH 4 have the next priority, and so on). Thus a case of low PU activity can assist the RECR-MAC protocol to select a reliable DCH when the CRAHN is initialised. However, in this chapter, the performance of RECR-MAC protocol is compared with other CR-MAC protocols without channel ranking criteria. Moreover, only BDC is considered to manage the PUs activity over the DCHs.

7.1 Parameters of the RECR-MAC and Benchmark CR-MAC Protocols

The conventional features of the wireless technology and its applications can be utilised for the deployment of the cognitive networks. It is important to carefully select the parameters of the wireless networks because these parameters can control multiple features of the CR-MAC protocols. For example, the size of the packet, available time for the SUs, channel capacity, probability of the successful access of control and data channels and switching time among the SUs over the DCH. If the length of the frame is higher than the available time over the DCH for the SUs, then the transmitting SUs are unable to continue the transmission of the frames and receive the ACK message from the receiving SUs which require re-transmission and decrease the network performance. In this research, the IEEE 802.11b parameters are used as a benchmark to implement the RECR-MAC and other CR-MAC protocols. The Distributed Coordination Function (DCF) uses the CSMA/CA mechanism to access the DCCH. There are following reasons to select the IEEE 802.11b parameters:

1. The 802.11b parameters have been used to develop the modelling and simulation of most of the existing well known CR-MAC protocols [57] [20] [73] [58] [24] [78] [21] [23].
2. The parameters of IEEE 802.11b are extensively deployed, implemented and utilised by the research community and industry.
3. The parameters of IEEE 802.11b can be simulated by different models of different simulation tools such as MATLAB [159], OPNET [179], NS-2 [180] and OMNET [181].

In this chapter, the RECR-MAC protocol is simulated by MATLAB for different scenarios with a varying number of PUs, SUs, DCHs, data size and different ON/OFF traffic patterns. The variation of these factors shows the performance and validity of the RECR-MAC protocol and its comparison with other CR-MAC protocols. The parameters shown in Table 7.1 are utilised in the MATLAB simulation which will observe the activity of the PUs; record the free time for the SUs communication, calculate the communicating time; and compute the transmitting energy and throughput among the SUs.

TABLE 7.1: Parameters for design and analysis of the RECR-MAC protocol

Parameters	**Values**	**Description**
ACL	25 Bytes	The length of available channel list frame
AACL	13 Bytes	The length of ACK of available channel list frame
SIFS	10 μs	Short inter-frame space
DIFS	50 μs	DCF inter-frame space
SU_n	2-10	Number of secondary users (varies from 2 to 10 SUs)
T_xR_x	2	Two transceivers for exchanging control and data frames
DCH	2-10	Data channels vary from 2 to 10 for data communication
P_L	140-202 Bytes	Payload (Each experiment has a different payload for validation)
D_{Rate}	11 Mbps	Transmit rate for control and data channels
T	Varies	Communication time over the control and data channels always varies based on the payload, number of SUs, wait time, etc.
P_{FA}	0.1	Probability of false alarm
CW	32	Contention Windows (range from 16512)
Ack	14 Bytes	Acknowledgment after successful exchange of control and data information
τ	5 μs	Switching time over the data channel (if PU returns)
Simulation Time	12.6 ms	The simulation time is 12.6 ms for the proposed RECR-MAC and benchmark CR-MAC protocols. A pair of SU has to exchange their control and data frames within 2100 μs for each simulation run.
$P_{transmitting}$	300 mW	Transmitting power

The following Table 7.2 shows the main contributing parameters of the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols. These parameters are used in the simulation for comparison with the RECR-MAC protocol.

7.2 Performance Evaluation

Several simulation based experiments will be discussed in the following sub-sections where multiple pairs of SUs, such as 2, 4, 6, 8 and 10, access the control and data channels, and exchange multiple

TABLE 7.2: Parameters for design and analysis of the CR-MAC protocols for comparison

Parameters	**Values**	**Description**
RTS	20 Bytes	The length of ready to send frame
CTS	20 Bytes	The length of clear to send frame
SIFS	10 μs	Short inter-frame space
DIFS	50 μs	DCF inter-frame space
SU_n	2-10	Number of secondary users (varies from 2 to 10 SUs)
T_xR_x	Vary	Number of transceivers based on the protocol characteristics
DCH	2-10	Data channels vary from 2 to 10 for data communication
P_L	140-202 Bytes	Payload (Each experiment has a different payload for validation)
D_{RATE}	11 Mbps	Transmit rate for control and data channels
T	Varies	Communication time over the control and data channels always varies based on the payload, number of SUs, wait time, etc.
P_{FA}	0.1	Probability of false alarm
CW	32	Contention Windows (range from 16512)
Ack	14 Bytes	Acknowledgment after successful exchange of control and data information
τ	5 μs	Switching time over the data channel (if PU returns)
CST	20 Bytes	Channel state transmitter
CSR	20 Bytes	Channel state receiver
FRQ	20 Bytes	Frequency request
FRP	20 Bytes	Frequency response
ACK_{hello}	16 Bytes	Ack. hello used in DSA-MAC for acknowledgement
RTS_{Switch}	20 Bytes	The length of ready to send for SWITCH protocol
CTS_{Switch}	16 Bytes	The length of clear to send for SWITCH protocol
NTS_{Switch}	16 Bytes	The notification to reserve the BDC in SWITCH
EB	20 Bytes	The length of emergency beacon for RMC protocol
HB	20 Bytes	The length of handoff beacon of RMC protocol

sizes of data frames. Moreover, each CRN consists of 10 pair of PUs. The DCCH of each benchmark protocol requires from 430 μs to 800 μs for exchanging only control frames among the SUs without any PU interference [57] [20] [58] [23]. Furthermore, there is an additional time required to transmit the data between senders and receivers. Each experiment takes 12.6 ms including 6 runs, where each run takes 2100 μs. During the first run, SUs only record the PUs activity and in the remaining five runs exchange the control and data frames. The CCH is dedicated and always available for all SUs for exchanging their control information. Based on IEEE 802.11b, data rate of the control and data channels is set to 11 Mbps and channel Switching Time (τ) between the DCHs is 5 μs, transmitting power ($P_{transmitting}$) is set to 300mW [24], and a circular field with radius of 100 meters is set. Based on the 2012 migration from analogue to digital of the TV system in the United Kingdom, more than 70% of TV spectrum bands are unused and underutilised as discussed in Chapter 1. According to the UK white spaces statistics [182], the TV spectrum bands from 470 MHz to 790 MHz are available most of the time and can be effectively utilised for the CRNs. Therefore, I am considering the TV spectrum bands from 470 MHz to 591 MHz, which contain 11 channels. The bandwidth of each channel is 11 Mbps. The channel 1 is assumed and dedicating for controlling the control frames and the rest of the channels can be utilised for the data communication. Five simulation based experiments are conducted to validate the performance of the RECR-MAC protocol and its comparison with benchmark CR-MAC protocols.

In experiments 7.2.1 and 7.2.2, the RECR-MAC and benchmark CR-MAC protocols select two DCHs for exchanging the data frames with and without PU returns. However, in experiments 7.2.3 to 7.2.5, the RECR-MAC and other benchmark CR-MAC protocols exchange their control and data frames according to their functionality. Further details of simulation results are discussed under each experiment.

7.2.1 Experiment 1: Simultaneous Communication over two DCHs with NO PU Returns

In this experiment, 10 DCHs are available to accommodate 10 SUs, 10 PU pairs, and data size of 1280 bits (160 characters). At the beginning of the simulation, the receivers of each participating SU records the activity of the PUs on each DCH. First pair of SUs select two most reliable DCHs among the 10 available DCHs. At the startup, all DCHs have no ranking and history of the communication, which shows that the network is initialized. Therefore, the DCHs are organized with the values from 1 to 10 based on the maximum free time available over each DCH for the SU usages. After organizing the reliable channel list, the next step is to select the primary and backup data channels for data transmission. The DCH with least PU activity and maximum availability of the free time for the SU is considered the most reliable channel named DCH 1. The DCH 2 has second priority after DCH 1, up to DCH 10. Figure 7.1 shows the activity of the PUs over each DCH. The x-axis represents the time in microseconds of the PUs activity. The y-axis represents the activity of the PUs in the ASCII (American Standard Code for Information Interchange) format. The ASCII character has no unit. The discussion of the PUs traffic pattern is beyond the scope of this thesis, and it provides the information about the availability or unavailability of the PUs over the DCHs only. The SUs select the DCHs based on these PUs activities.

For the comparison purpose, it has been assumed that all benchmark CR-MAC protocols (such as CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC) transmit simultaneously over two DCHs like RECR-MAC protocol. These benchmark CR-MAC protocols are not originally designed to transmit over two DCHs simultaneously. In Figure 7.1, the PU turns ON from 0 to 400 μs, turns OFF from 401 μs to 2080 μs, and turns ON again from 2081 μs to 2100 μs for DCH 1. Therefore, SUs have an opportunity to transmit the information over DCH 1 during the period of PUs OFF which is 401 μs to 2080 μs. The DCHs from 2 to 10 also have PUs activity from ON to OFF then to ON with different timing for the validation of the protocol performance and its simulation results. The SUs also have an opportunity to utilise these unused spaces over DCH 2 to DCH 10. According to the Figure 7.1, DCHs 1 and 2 are the most reliable channels among the available channels based on their maximum available free time for the SUs exchanging their control and data frames.

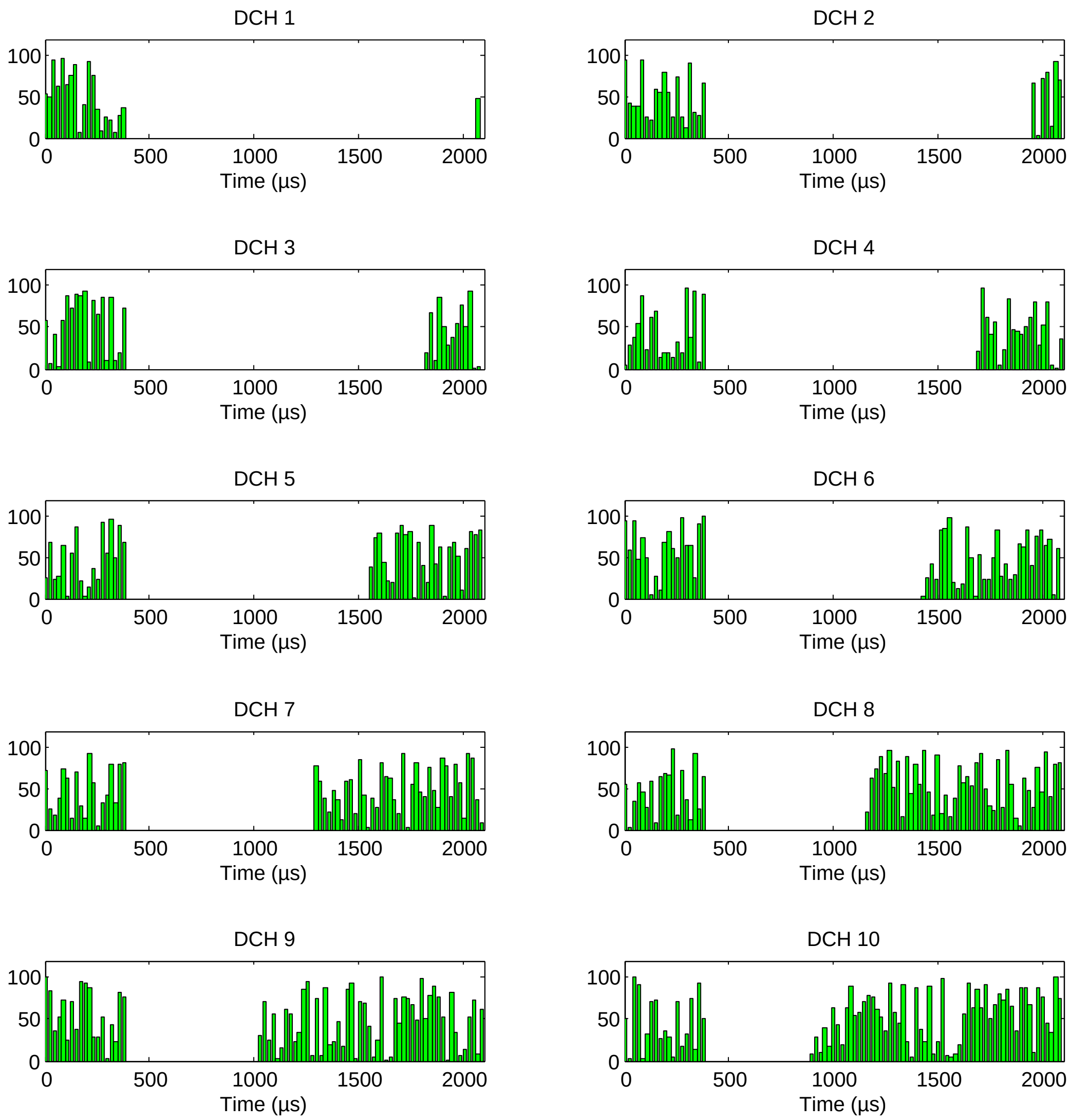

FIGURE 7.1: PUs activity over 10 DCHs

Based on the proposed design and framework of the RECR-MAC protocol, initially first two SUs participate to exchange control and data frames over the DCCH, DCH 1 and DCH 2. The SUs utilise approximately 437 μs over the DCCH to exchange their control frames including the ACK frame. In Figure 7.2, the red lines indicate the SUs traffic over DCH 1 and DCH 2, known as the PDCs, where SUs successfully exchange their information without any PU returns. The selection of the reliable DCHs based on the channel ranking has been discussed in detail in Chapter 4.

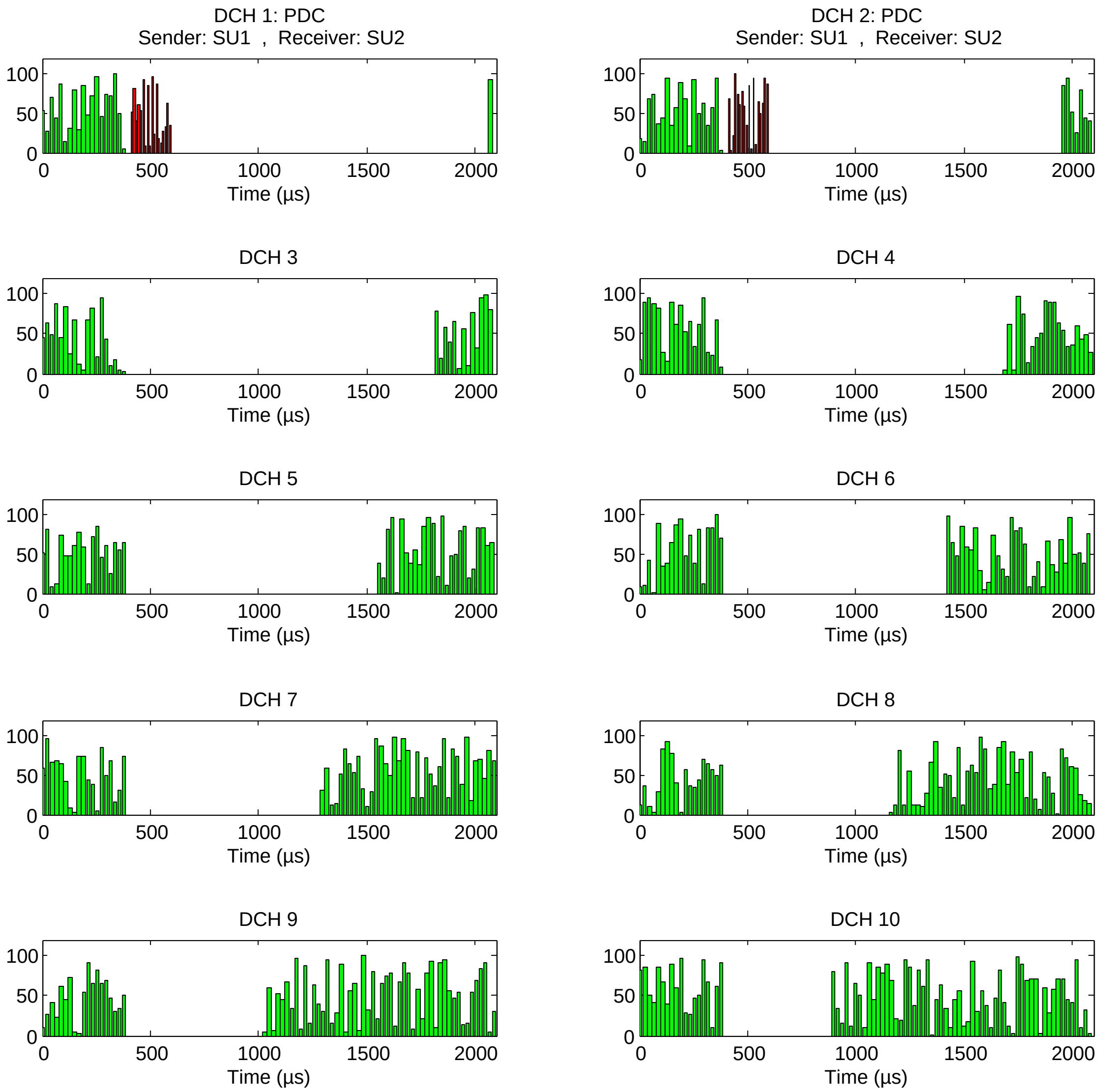

FIGURE 7.2: PUs activity over DCHs and SUs activity over DCHs 1 and 2

Figure 7.3 depicts the communication (comm.) time and energy consumed, which is utilised during the exchange of control and data frames between two SUs over PDC 1 and PDC 2. The results below show that the RECR-MAC protocol utilises less communication time and energy as compared to other benchmark CR-MAC protocols; even though all benchmark CR-MAC protocols select two DCHs for simultaneous transmission. Figure 7.3 shows the comparison of communication time and transmitting energy utilised by the RECR-MAC and other CR-MAC protocols.

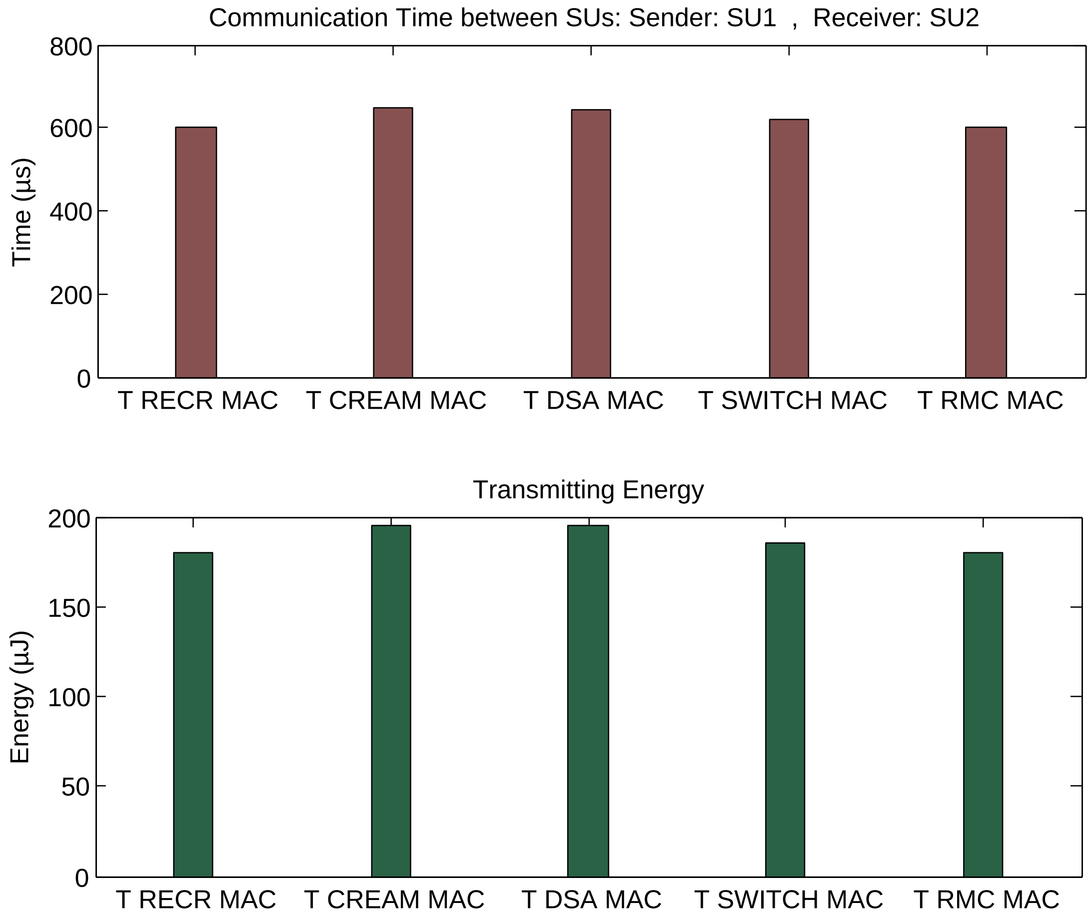

FIGURE 7.3: Communication time and transmitting energy consumed for CR-MAC protocols with two SUs

The simulation executes for the second time with 2 SUs, the third time with 4 SUs, the fourth time with 6 SUs, the fifth time with 8 SUs and the sixth time with 10 SUs. For the simplicity, Figure 7.4 represents the results of the sixth (final) run for the RECR-MAC protocol along other CR-MAC protocols. The simulation can be executed more or less than six times for each experiment; however, in this chapter, it is restricted to run for six times for 10 SUs in order to avoid keeping the long history of DCHs which may provide the old information of the channel's condition and mislead the SUs. The first two SUs access the DCCH without any waiting and exchange their control information and switch to DCHs for communication as shown in Figure 7.4. The remaining four pairs of SUs have to set their NAV timers and access the DCHs after their waiting times expire. The waiting time appears as a gap between the green and red lines over the DCHs. If the number of SUs is higher than the number of available DCHs, then the waiting SUs require to wait for the participating SUs to complete their communication to avoid collision. However, it may be possible that the PU returns over that DCH during the communication, which increases the communication time. It is also possible that the participating and ongoing SUs collide each other, but the sensor of each SU updates its record and does not switch to that DCH to avoid collision and avoid re-start of the entire process. To conclude, all 10 SUs have successfully exchanged their control and data information. The SUs 1 and 2 have communicated over DCHs 3 and 4, SUs 3 and 4 have communicated over DCHs 7 and 8, SUs 5 and 6 have used DCHs 9 and 10, SUs 7 and 8 have exchanged information over DCHs 5 and 6, and SUs 9 and 10 have exchanged information over DCHs 1 and 2.

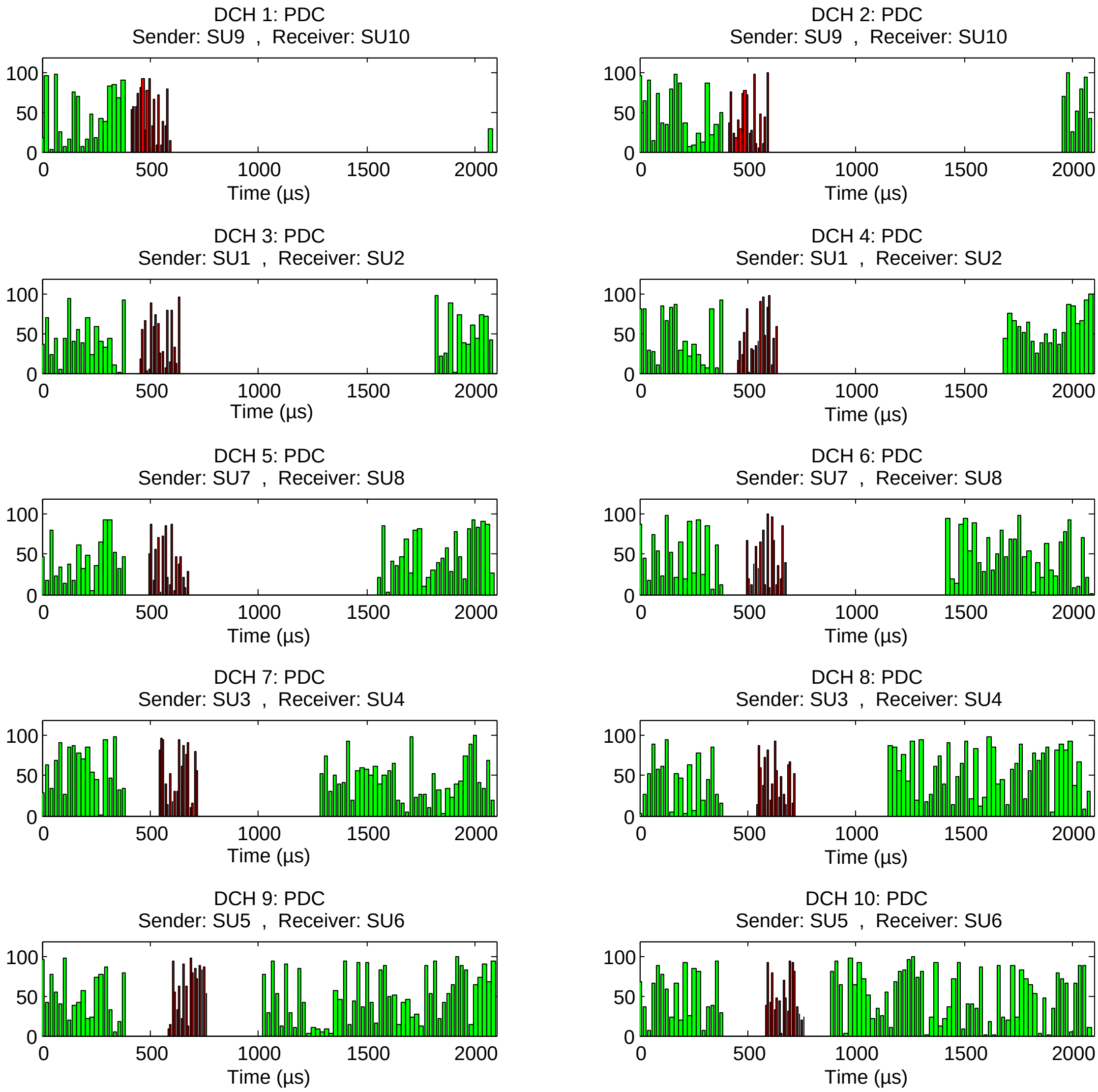

FIGURE 7.4: PUs and SUs activity over 10 DCHs

As shown in Figure 7.5, the RECR-MAC protocol utilises less communication time and transmitting energy as compared to the benchmark CR-MAC protocols during the entire process in this simulation.

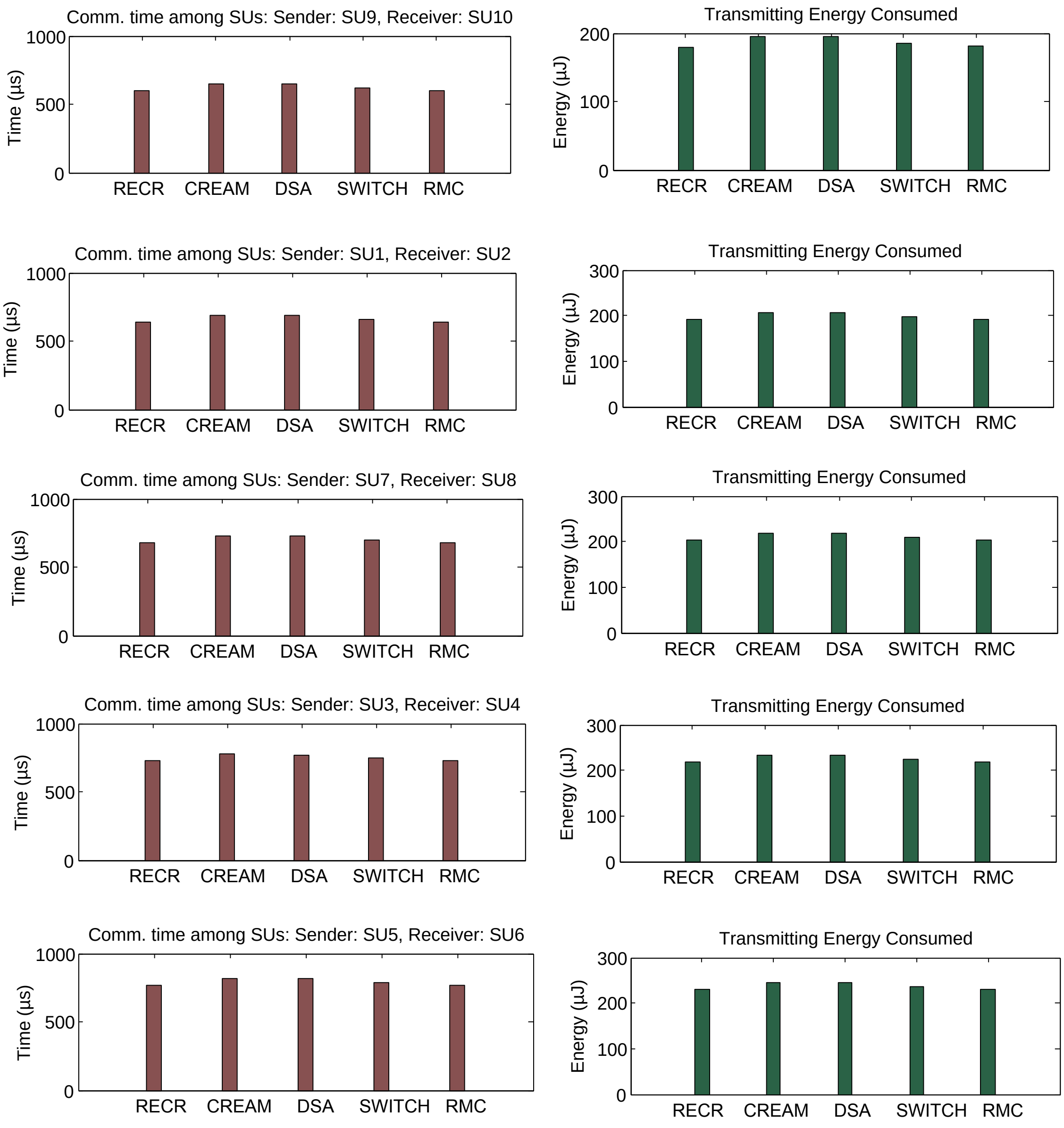

FIGURE 7.5: Communication time and transmitting energy consumed for CR-MAC protocols with 10 SUs

Figure 7.6 shows the communication time consumed by 2, 4, 6, 8 and 10 SUs, where the x-axis represents the number of SUs and the y-axis represents the time consumed for different pairs of SUs. It demonstrates that the RECR-MAC protocol utilises slightly less time to exchange its control and data information as compared to other CR-MAC protocols. By considering 10 SUs, the RECR-MAC protocol saves approximately 0.3%, 2.9%, 6.6% and 6.9% communication time as compared to RMC-MAC, SWITCH-MAC, DSA-MAC and CREAM-MAC protocols respectively. To conclude, the RECR-MAC and other CR-MAC protocols have utilised two DCHs for simultaneous communication, but it has clearly indicated that the RECR-MAC protocol requires slightly less communication time as compared to other CR-MAC protocol with no PU returns. During the first run, only 2 SUs have communicated over control and data channels and utilised approximately 599 to 650 μs. In addition, during the 2nd run, 4 SUs participated, 3rd run, 6 SUs participated, 4th run, 8 SUs participated and 5th run, 10 SUs participated and utilised approximately 3400 3700 μs communicating time for exchanging their control and data information without PU returns.

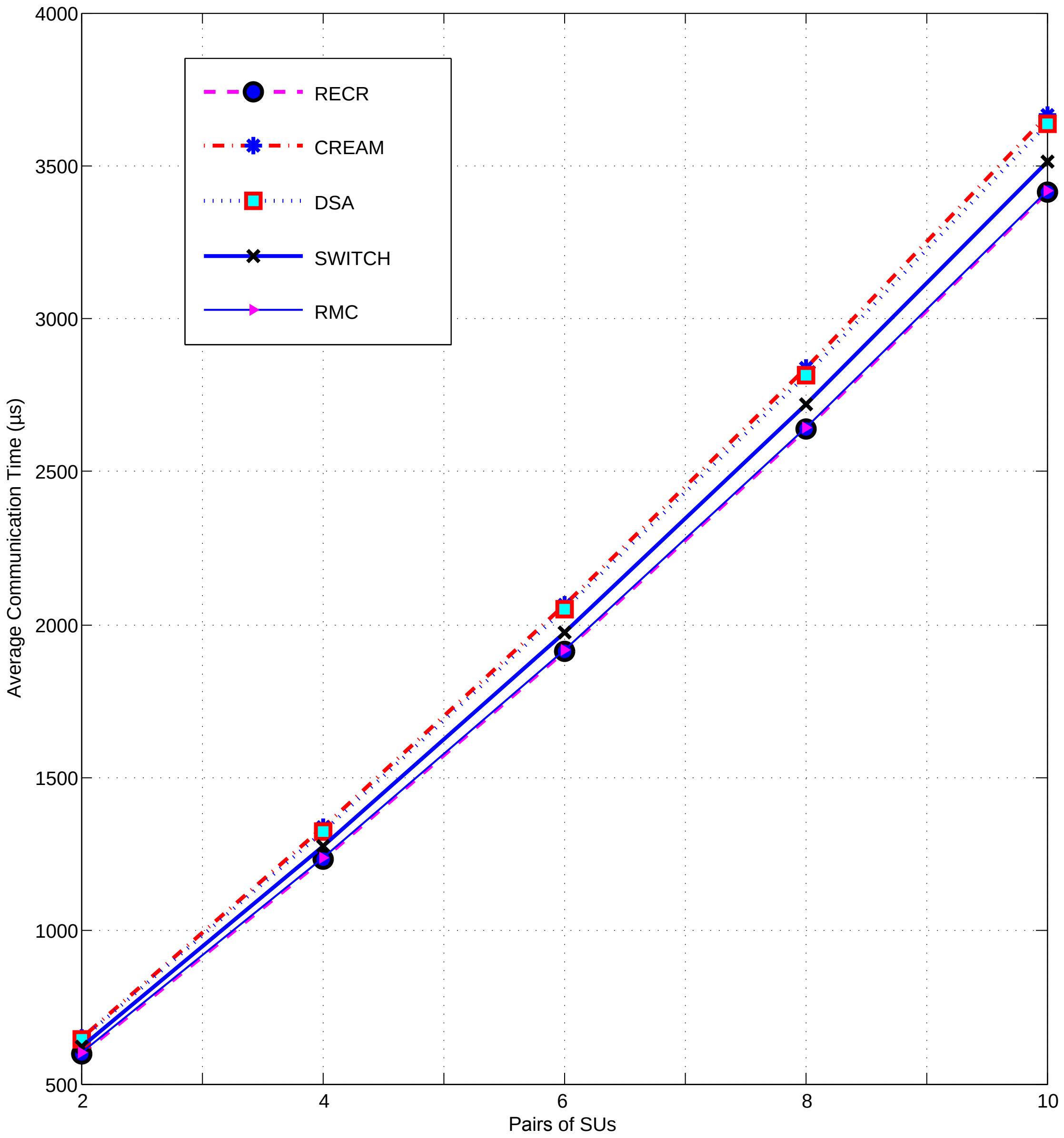

FIGURE 7.6: Communication time consumed by CR-MAC protocols vs pairs of SUs

In Figure 7.7, the transmitting energy consumed by 2, 4, 6, 8 and 10 SUs, where the x-axis represents the number of SUs and the y-axis represents the transmitting energy utilised for multiple pairs of SUs. It indicates that the RECR-MAC protocol transmits slightly less energy to exchange control and data information as compared to other CR-MAC protocols. To conclude, RECR-MAC saves 0.3%, 2.9%, 6.6% and 6.9% transmitting energy as compared to RMC-MAC, SWITCH-MAC, DSA-MAC and CREAM-MAC protocols without any PUs return during the communication for 10 SUs.

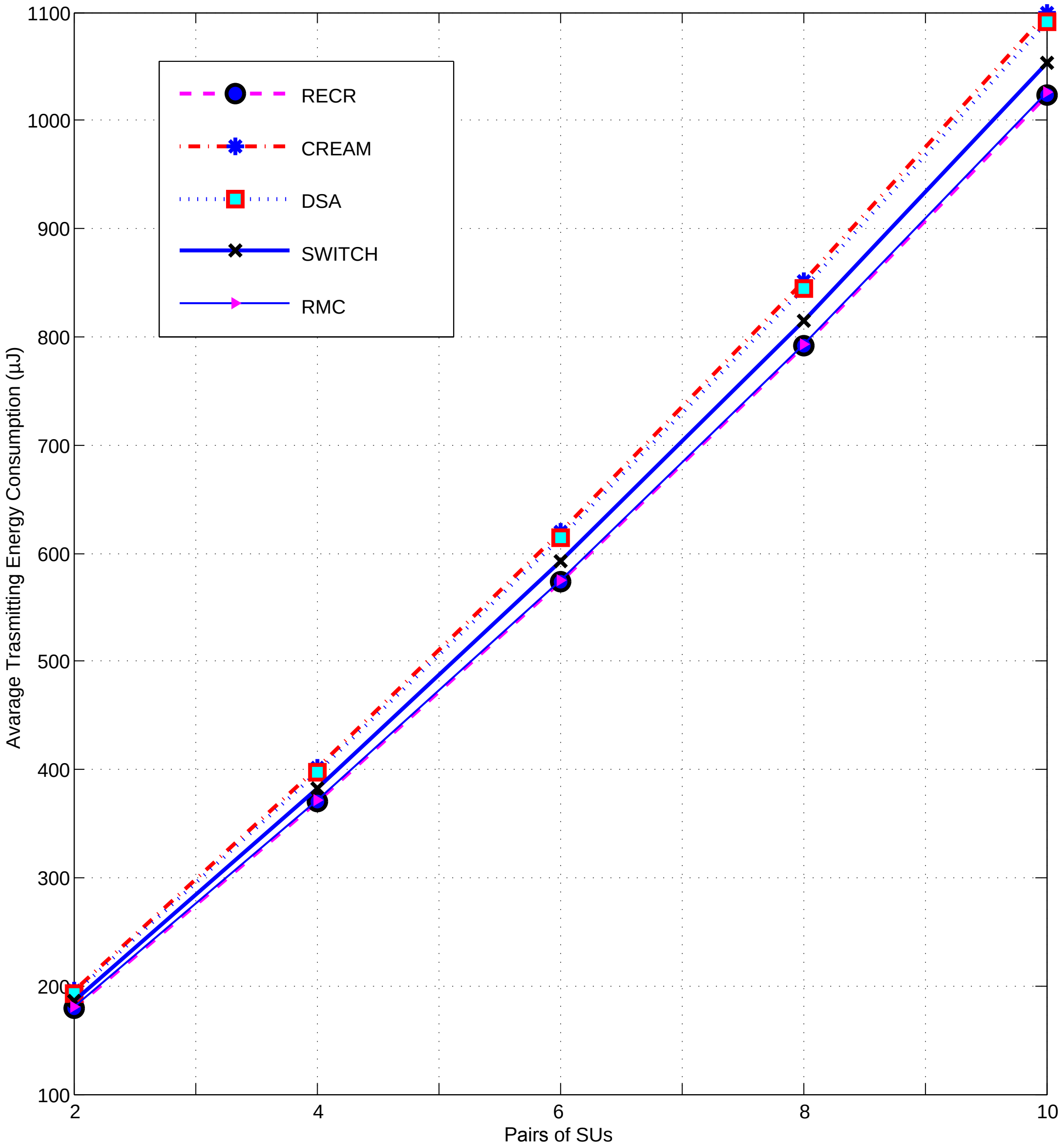

FIGURE 7.7: Transmitting energy consumed by CR-MAC protocols vs pairs of SUs

Table 7.3 indicates that the RECR-MAC protocol utilises less communication time and transmitting energy as compared to benchmark CR-MAC protocols without PU returns during the communication.

Figure 7.8 depicts the throughput comparison of the RECR-MAC protocol with other CR-MAC protocols, and it shows that the RECR-MAC protocol achieves more than 50% higher throughput as compared to the benchmark CR-MAC protocols. The results below verify the validity and functionality of the proposed RECR-MAC protocol.

TABLE 7.3: Communication time and transmitting energy values utilised by 10 SUs without PU returns

	RECR	CREAM	DSA	SWITCH	RMC
Communication Time Utilised (μs)	3412	3664	3653	3513	3419
Energy Transmitting (μJ)	1023	1099	1091	1054	1026

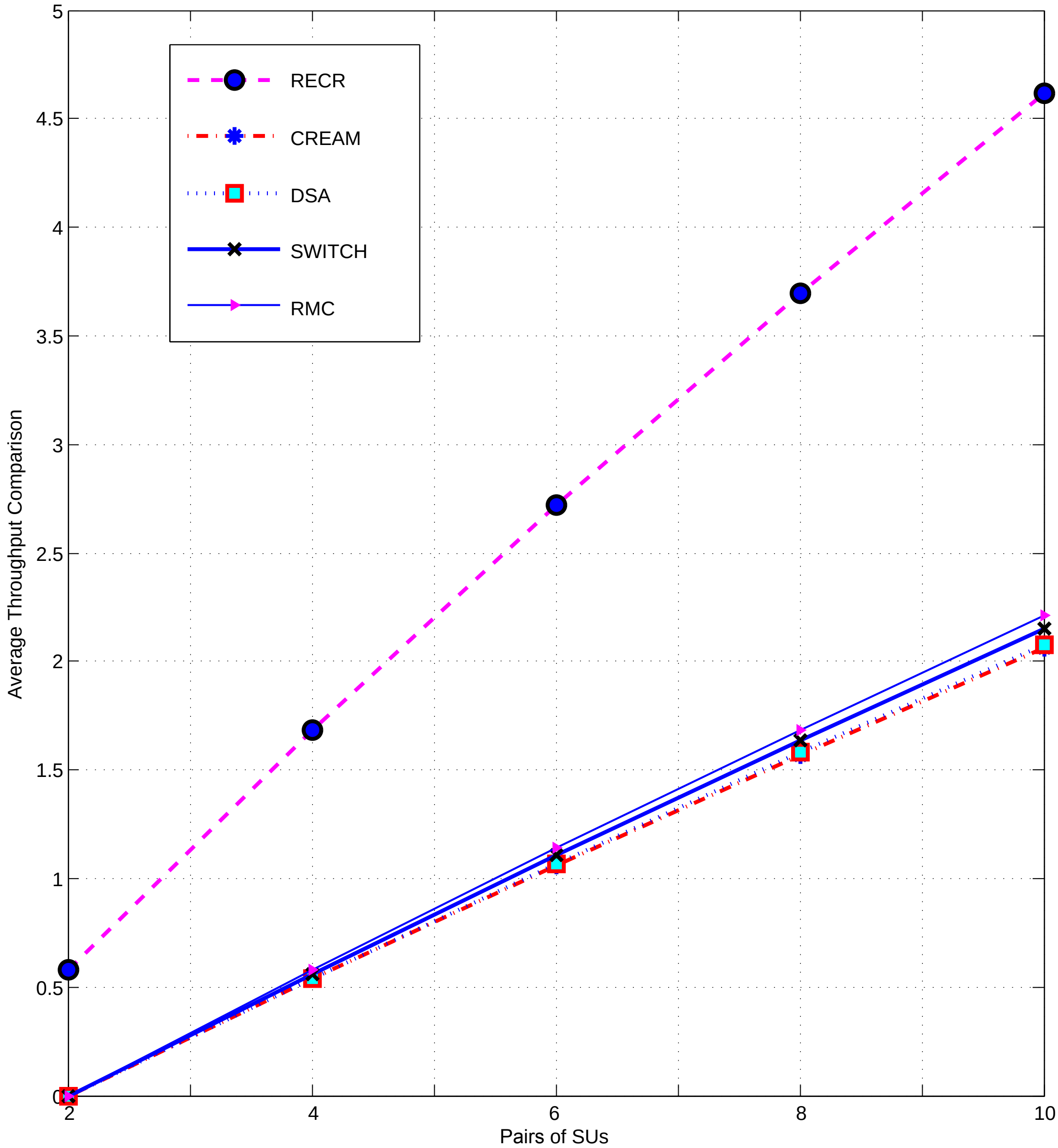

FIGURE 7.8: Average throughput comparison of CR-MAC protocols vs pairs of SUs

To conclude, in this experiment there were 10 DCHs, 5 PU pairs, 10 SUs and 1280 bits of data which were simulated for 2100 μs over the control and data channels. All CR-MAC protocols have utilised two DCHs simultaneously for the transmission of their data information. The results in Figures 7.1 to 7.8 have indicated that the RECR-MAC protocol utilises reduce communication time, consumes less transmitting energy and has a higher throughput as compared to the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols.

7.2.2 Experiment 2: Simultaneous Communication over two DCHs with PU Returns

Most of the parameters used in this experiment are same as those used in experiment 7.2.1 except the PUs ON/OFF timings and PU returns over the DCHs during the communication. Table 7.4 shows the ON/OFF timings of PUs and SUs. Figure 7.9 illustrates the activity of the PUs over the DCHs and corresponds to the PUs and SUs ON/OFF timings mentioned in Table 7.4. The PUs have first priority to use the licensed spectrum bands and SUs can only utilise the gaps left by the PUs.

Table 7.4: PUs/SUs ON and OFF Timings over DCH 1

Timings (μs)	**0-200**	**201-500**	**501-800**	**801-1200**	**1201-1600**	**1601-1800**	**1801-2100**
PU ON (SU OFF)	$\surd$		$\surd$		$\surd$		$\surd$
SU ON (PU OFF)		$\surd$		$\surd$		$\surd$	

Figure 7.9 shows the PUs activity over DCHs 1 to 10. Applying the CR rules to the adhoc wireless network, the SUs are only allowed to utilise the gaps among the PUs such as 201 to 500 μs, and 801 to 1200 μs, etc. Initially, it is noticed that there are no SUs activities over the DCHs. According to the reliable channel selection strategy, highest free time is marked as most reliable DCHs and first pair of the SUs utilise these DCHs for their communication. The DCH 10 has high priority and DCH 1 has least priority as compared to other available DCHs. The ON/OFF activity of the PUs over the 10th DCH is depicted in Table 7.5.

Table 7.5: PUs/SUs ON and OFF Timings over DCH 10

Timings (μs)	**0-200**	**201-500**	**501-800**	**801-1200**	**1201-1600**	**1601-1980**	**1901-2100**
PU ON (SU OFF)	$\surd$		$\surd$		$\surd$		$\surd$
SU ON (PU OFF)		$\surd$		$\surd$		$\surd$	

Figure 7.9 shows the activity of the PUs, where SUs have an opportunity to use the free time for their transmission. The DCHs 10 and 9 have the highest priority as compared other available DCHs and an initial pair of the SU can use these channels to exchange their information based on channel selection criteria.

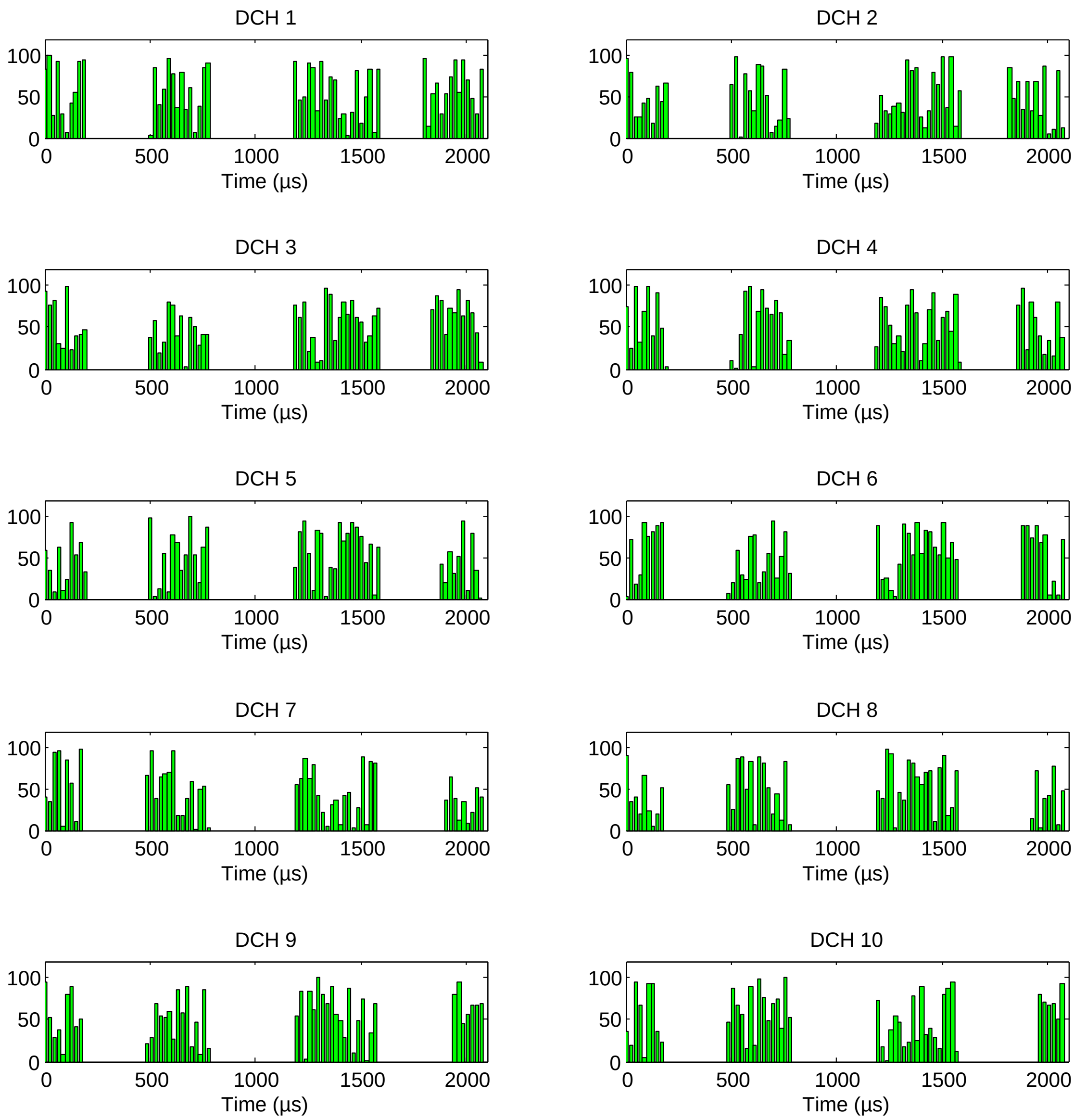

FIGURE 7.9: PUs activity over 10 DCHs

As discussed earlier, each SU has a sensor which records the PUs activity, returns of the PUs, and SUs communication over the DCHs. Based on the channel selection criteria, the SUs select the most reliable DCHs 10 and 9 for exchanging data information. In this experiment, the PUs are frequently turning ON/OFF and SUs are unable to transmit their entire data during the available free time as shown in Figure 7.10. Therefore, the SUs are able to hold the remaining part of the data and continue to transmit the remaining part of the data when PUs turn OFF again. The SUs start to transmit simultaneously over DCHs 10 and 9 after successfully exchanging of control information over DCCH.

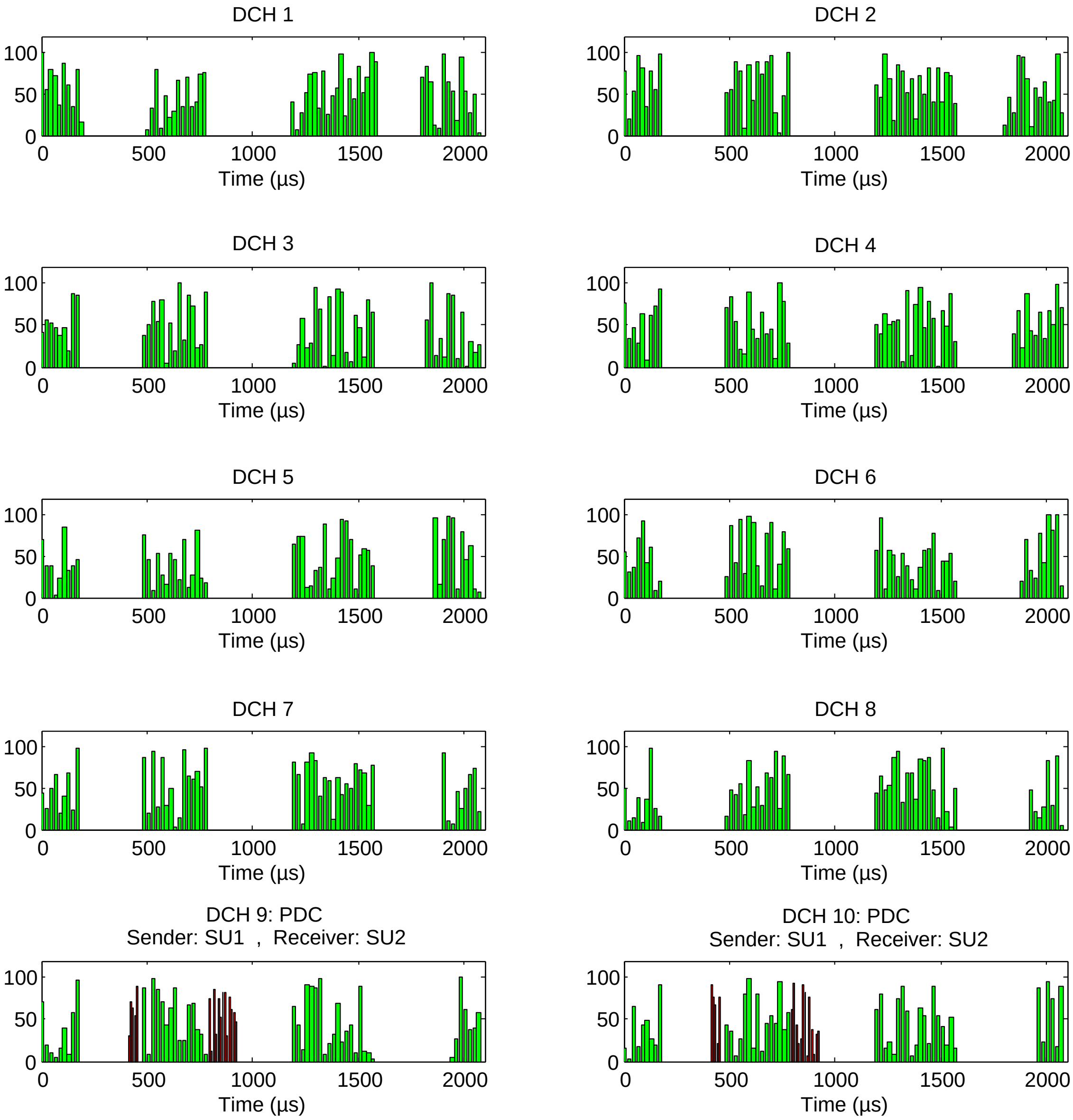

FIGURE 7.10: PUs activity over DCHs and SUs activity over DCHs 9 and 10

Figure 7.11 shows the consumption of time and transmitting energy for the RECR-MAC and the benchmark CR-MAC protocols. The transmitting energy is also set 300 mW for this experiment described in Section 7.2. Moreover, it provides the comparison results of the RECR-MAC protocol with other CR-MAC protocols.

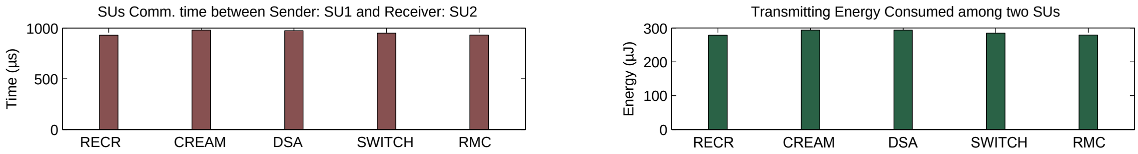

Figure 7.11: Communication time and transmitting energy consumed for CR-MAC protocols with 2 SUs

Similarly, the simulation is executed for the second time with 2 SUs, the third time with 4 SUs, the fourth time with 6 SUs, the fifth time with 8 SUs and the sixth time with 10 SUs. For the clarity and simplicity, in Figure 7.12, the results of the sixth (final) run for the RECR-MAC protocol along with the benchmark CR-MAC protocols are presented. The first 2 SUs access the DCCH and the SUs start to exchange their control information without any wait time, then switch to the selected DCHs for communication. The others 4 pairs of SUs have to wait until the NAV timer expires and no activity is reported by the sensor to the respective SU about those DCHs. To conclude, all 10 SUs successfully exchange their control and data information during the free time of PUs.

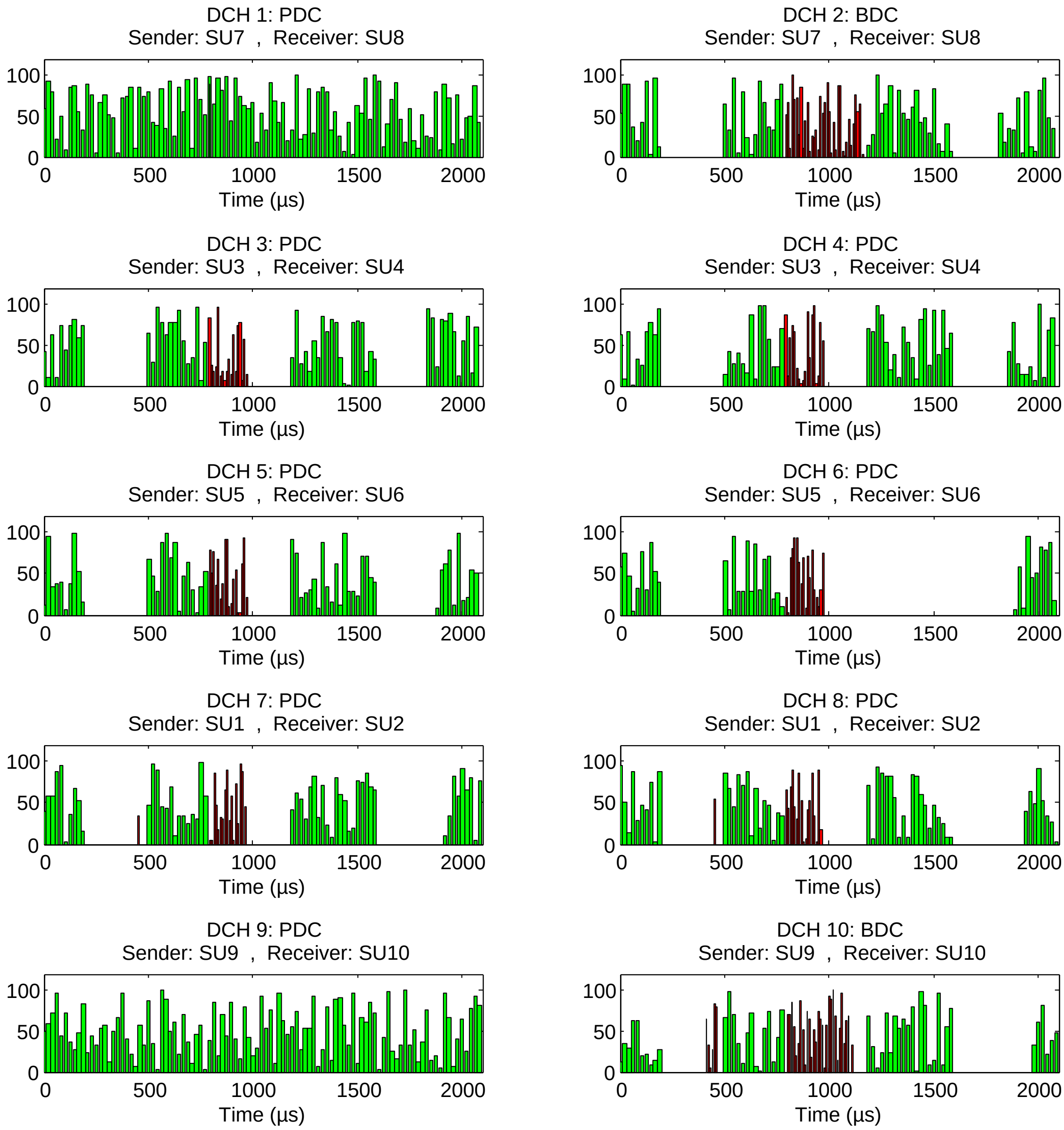

FIGURE 7.12: 10 PUs and SUs activity over DCHs

Figure 7.13 depicts the communication time and transmitting energy of 10 SUs during the simulation run. In addition, it shows the comparison of the RECR-MAC protocol with the benchmark CR-MAC protocols in terms of communication time and transmitting energy over DCHs. It also shows that SUs 9 and 10 initialize their communication over DCHs 1 and 2 and this process is continued until all 10 SUs transmit successfully their control and data frames. The results in Figure 7.13 prove that the RECR-MAC protocol utilises less communication time and transmitting energy during the entire process.

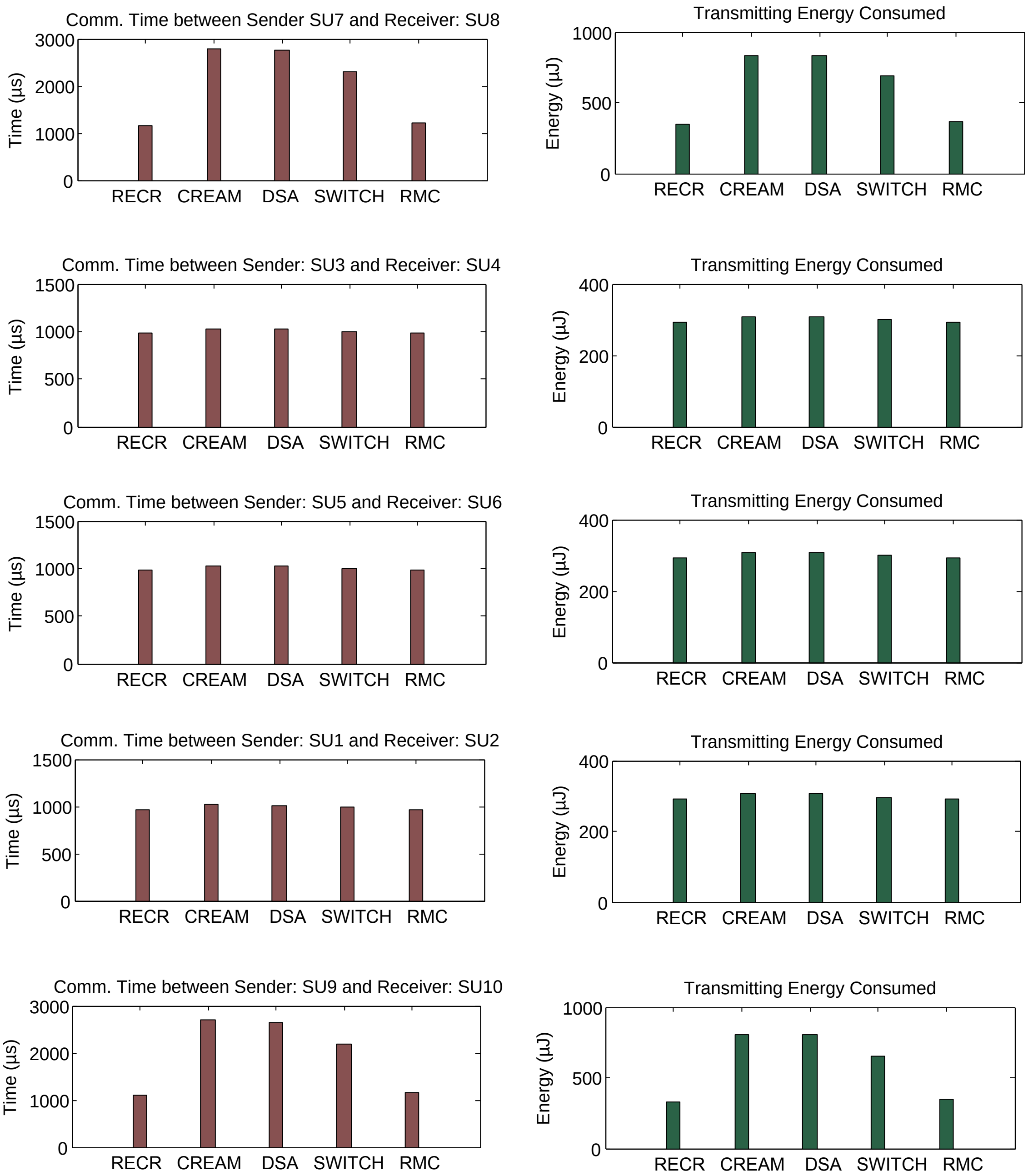

FIGURE 7.13: Communication time and transmitting energy for CR-MAC with 10 SUs

Figure 7.14 provides the comparison of communicating time used by 2, 4, 6, 8 and 10 SUs, where the x-axis represents the number of SUs and the y-axis represents the time consumed for different pairs of SUs. The obtained results show that the RECR-MAC protocol utilises slightly less time to successfully exchange its control and data information as compared to other benchmark CR-MAC protocols. By considering 10 SUs, the RECR-MAC protocol saves approximately 2%, 30%, 38% and

39% communication time as compared to RMC-MAC, SWITCH-MAC, DSA-MAC and CREAM-MAC protocols respectively. To conclude, the RECR-MAC and other benchmark protocols adopted similar approach for data communication over the DCHs. The PU returns over DCH 9 and SUs transmit their entire communication over DCH 10, as a BDC. The abrupt change in the graph of Figure 7.14 caused by the PU returns over DCH 9 and the SUs over the DCH 9 stays ON during the entire time. Thus, the results clearly indicate that the RECR-MAC protocol saves large communication time as compared to the benchmark CR-MAC protocols with PUs returns.

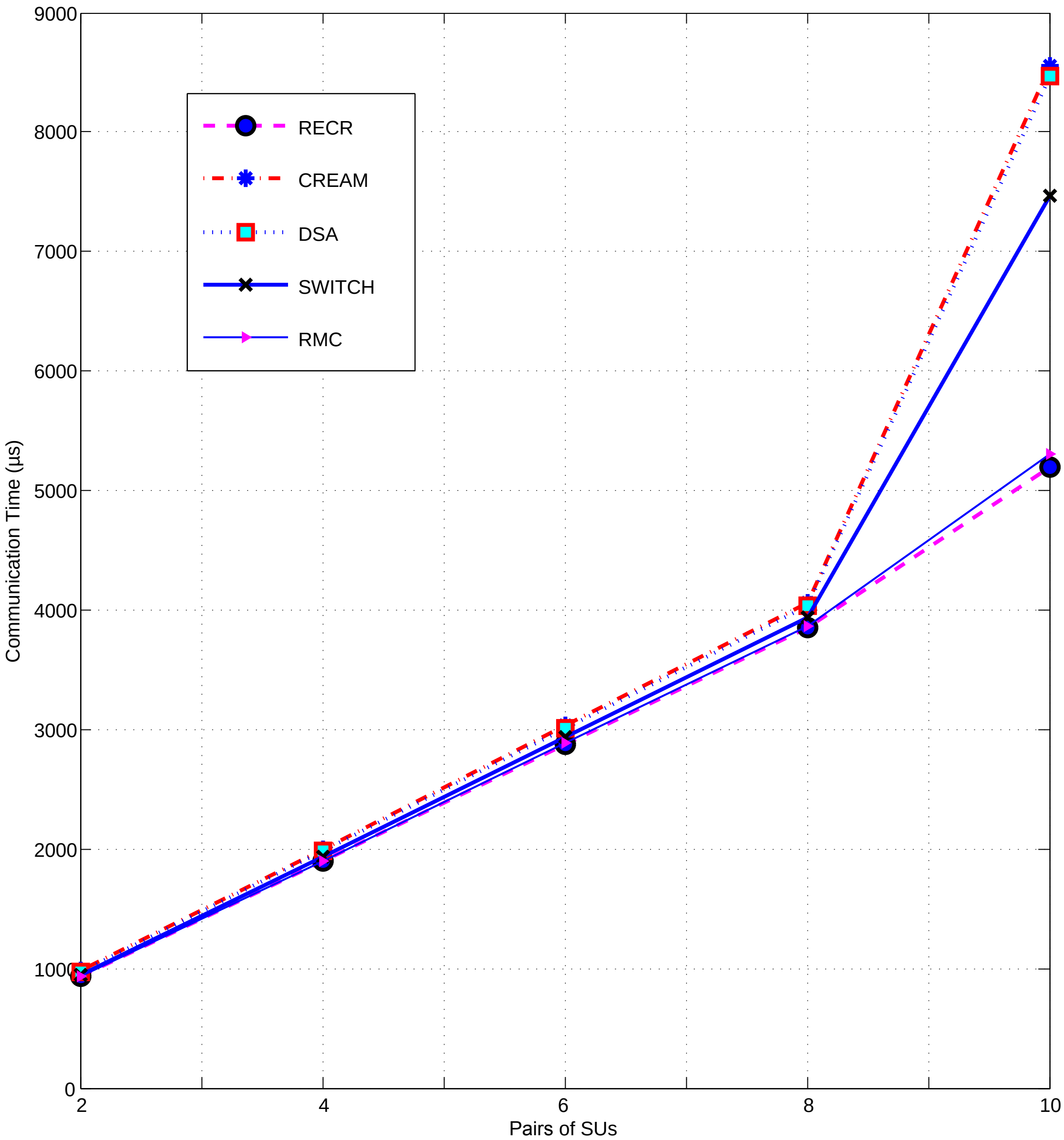

FIGURE 7.14: Communication time vs pairs of SUs of CR-MAC protocols

Figure 7.15 shows the transmitting energy consumed by 2, 4, 6, 8 and 10 SUs, where the x-axis represents the number of SUs and the y-axis represents the transmitting energy consumed for multiple pairs of SUs. By considering 10 SUs, the RECR-MAC protocol saves approximately 2%, 30%, 38% and 39% transmitting energy as compared to RMC-MAC, SWITCH-MAC, DSA-MAC and CREAM-MAC protocols respectively. There is an abrupt increase in the communicating time and transmitting energy among the SUs during the 4th run of simulation due to PU returns during the communication. The PU returns during the communication lead channel switching and restart the entire process. This process utilises additional transmission time and energy for exchanging the data frames among SUs. However, the obtained results indicate that the RECR-MAC protocol consumed less transmitting energy to exchange control and data information as compared to other benchmark CR-MAC protocols.

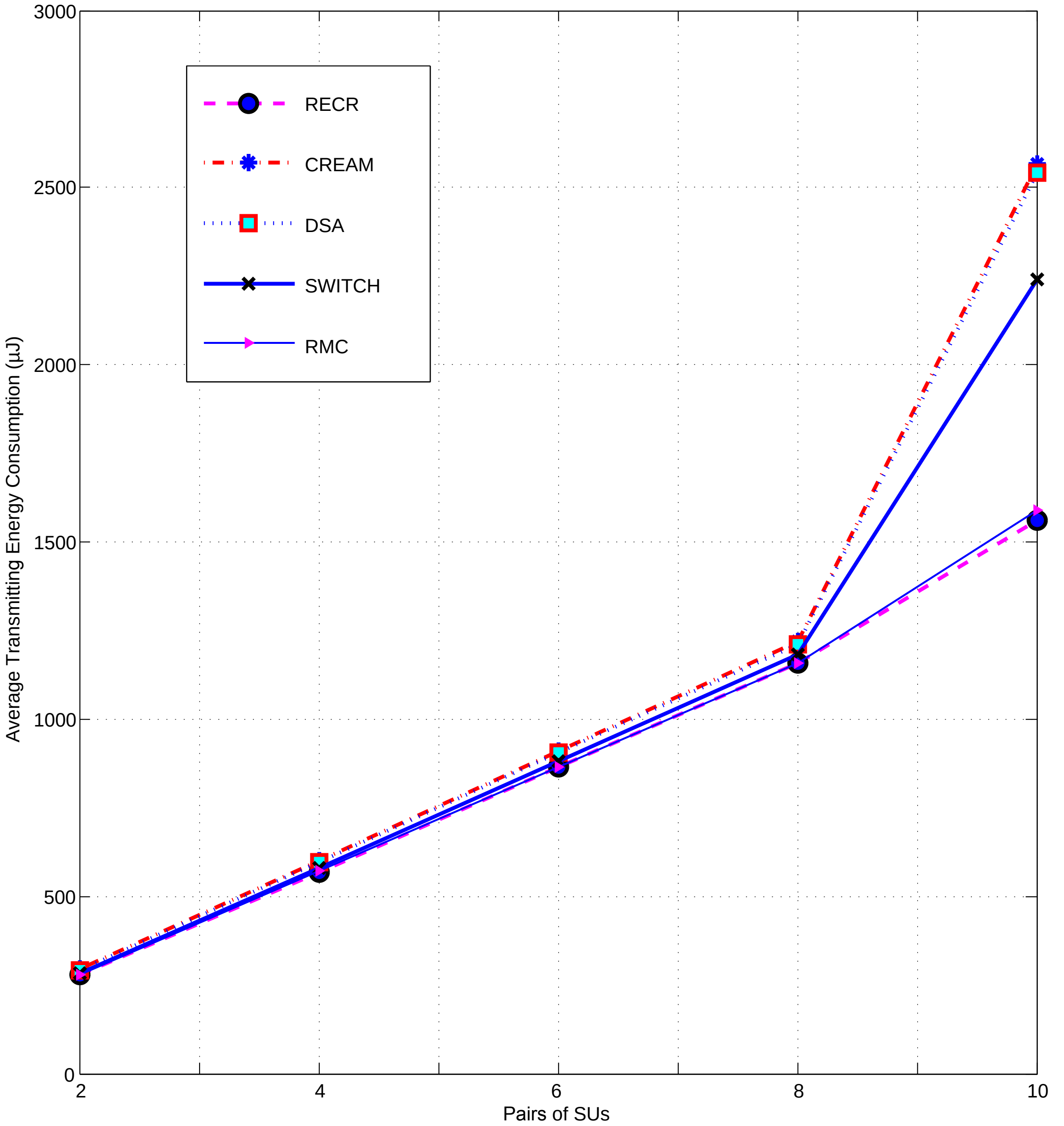

FIGURE 7.15: Transmitting energy consumed vs pairs of SUs of CR-MAC protocols

In addition, the values in Table 7.6 indicate that the RECR-MAC protocol utilises less communication time and transmitting energy as compared to the benchmark CR-MAC protocol.

TABLE 7.6: Communication time and energy values utilised by 10 SUs with PU returns

	RECR	CREAM	DSA	SWITCH	RMC
Communication Time Utilised (μs)	5199	8553	8469	7465	5305
Energy Transmitting (μJ)	1560	2566	2541	2240	1591

Figure 7.16 illustrates the throughput comparison among the RECR-MAC protocol with other benchmark CR-MAC protocols. The obtained results clearly show that the RECR-MAC protocol achieves more than 50% higher throughput when compared to other CR-MAC protocols, and verify the validity of the proposed RECR-MAC protocol and its implementation via simulation. The PU returns decrease the throughput of the benchmark CR-MAC protocols. However, the proposed RECR-MAC protocol is capable to manage the PU returns during the communication without degrading the throughput of the network.

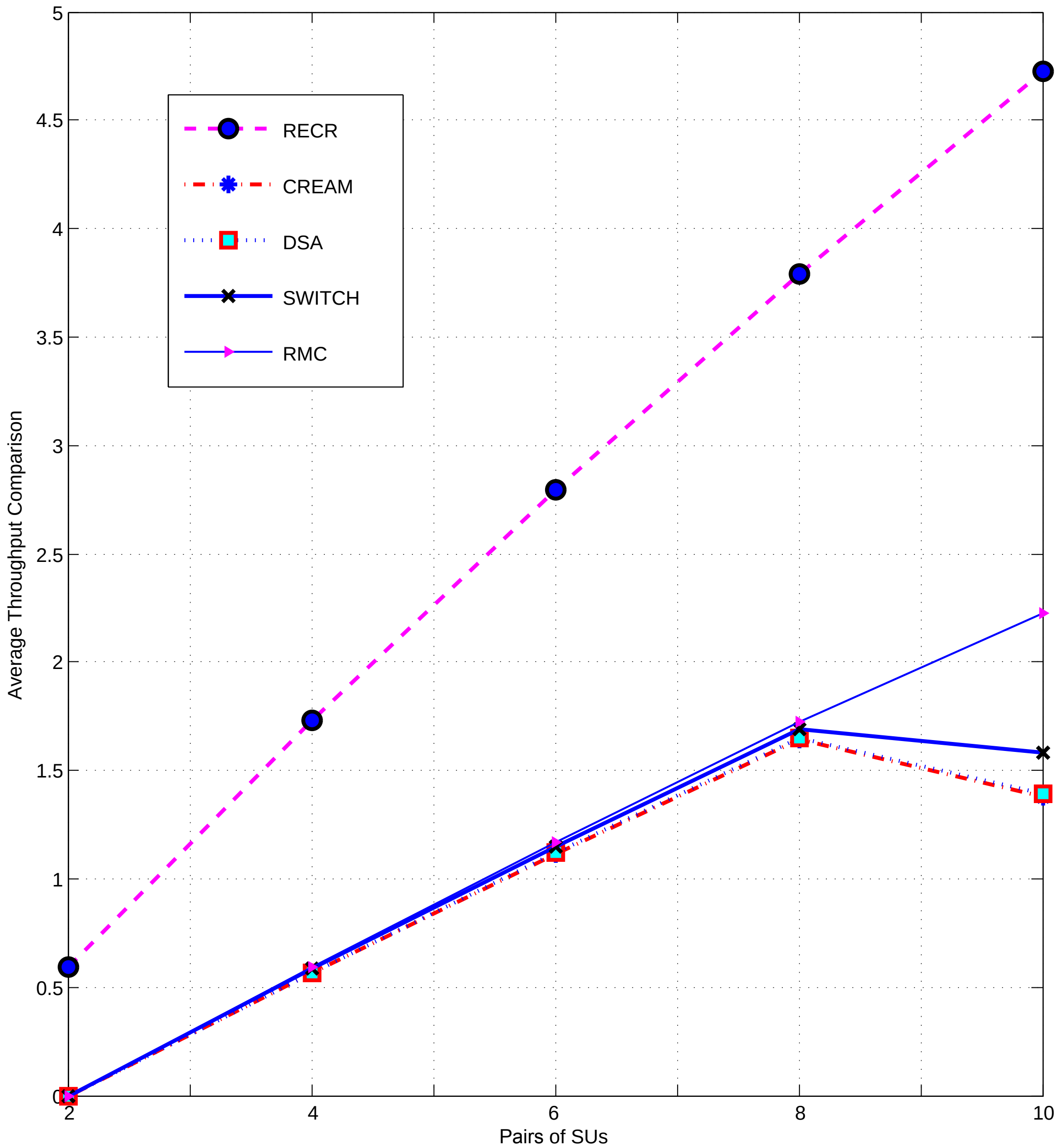

FIGURE 7.16: Average throughput comparison vs pairs of SUs of CR-MAC protocols

To conclude, 10 DCHs, 5 PUs pairs, 10 SUs and 1280 bits data have been simulated for the duration of 2100 μs. The comparison of the RECR-MAC and benchmark CR-MAC protocols clearly indicate the performance of the proposed framework and justifying the importance of the BDC. Thus, the RECR-MAC protocol utilises reduced communication time, consumes less transmitting energy and has a high throughput as compared to the CREAM-MAC, DSA-MAC, SWITCH-MAC and RMC-MAC protocols.

7.2.3 Experiment 3: Communication over DCHs with NO PU Returns

This experiment is performed based on the parameters in Tables 7.1 to 7.2 and experiment 7.2.1 with data size of 144 bytes, and under the assumption of no PU returns during the SUs communication over the DCHs. However, the RECR-MAC protocol selects two DCHs for simultaneous communication as discussed in Chapter 4, while the other benchmark CR-MAC protocols select their control and data channels as discussed in [57] [20] [58] [23]. The simulation runs for six times to validate the functionality of all selected CR-MAC protocols in this experiment. During the 1st run of the simulation, each SU sensor records the activity of the PUs on all DCHs. During the 2nd, 3rd, 4th, 5th, and 6th run, the SUs select their DCHs based on reliable channel selection criteria as discussed in Equation 4.1. Figure 7.17 shows the ON/OFF activity of the PUs over all DCHs. The SUs have an opportunity to utilise OFF time left by PUs and exchange their data frames over the unused spaces.

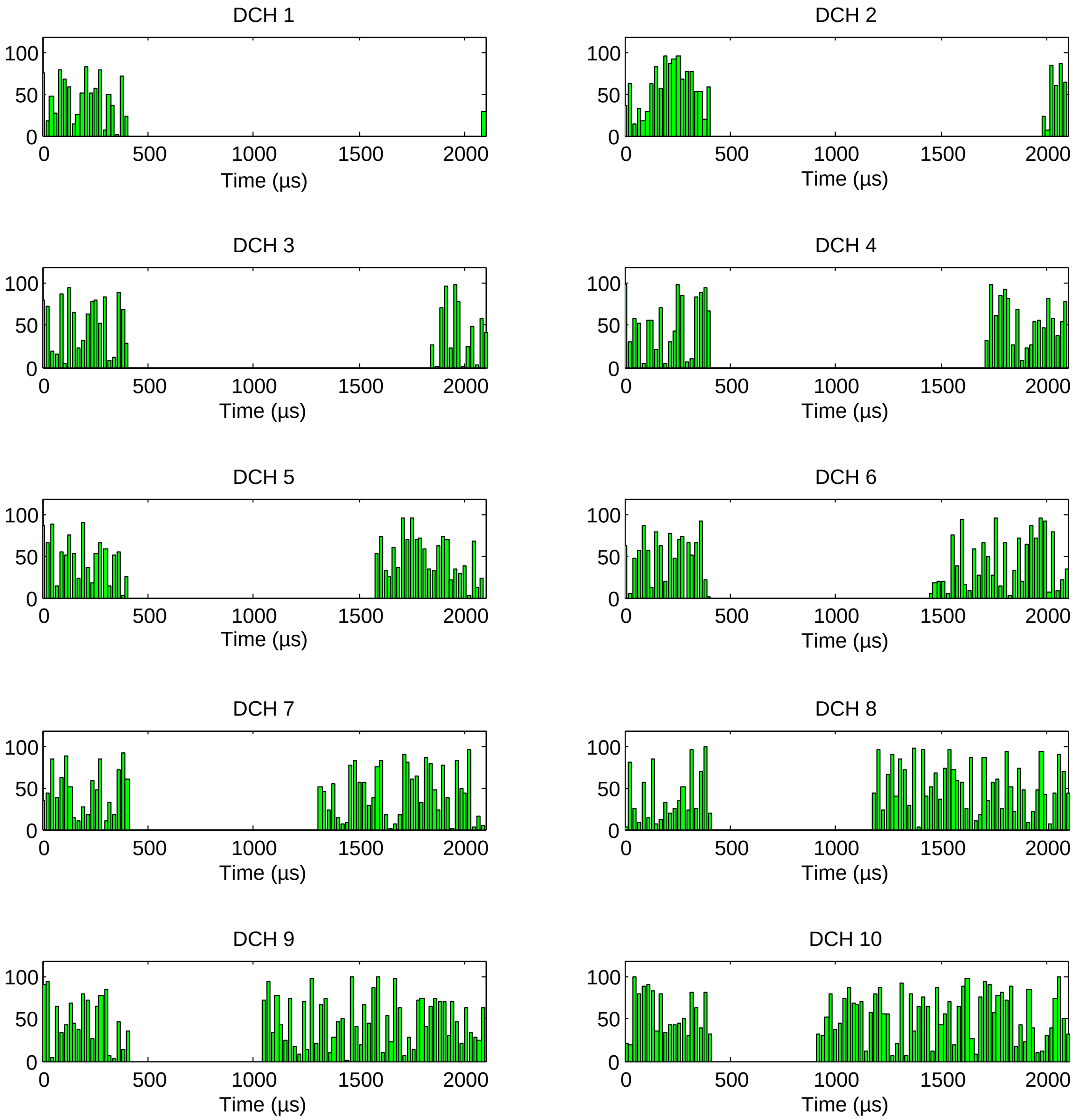

FIGURE 7.17: PUs activity over the DCHs

According to Figure 7.17, DCH 1 has a maximum and DCH 10 has minimum available free time for contributing SUs exchange of control and data frames. Therefore, DCH 1 has high reliability in terms of available maximum free time for the SUs to exchange data frames and vice versa for DCH 10. During the 1st run of the simulation, each participating SU sensor records the activity of the PUs over the DCHs. During the 2nd run of the simulation as shown in Figure 7.18, only one pair of SU is participating over the two most reliable DCHs named as DCH 1 and DCH 2. It is important to note that the SUs must exchange their control information and agree on the reliable

DCHs among each other before starting their communication. Figure 7.18 illustrates the activity of SUs during the OFF time of PUs and successful exchange of their control and data frames.

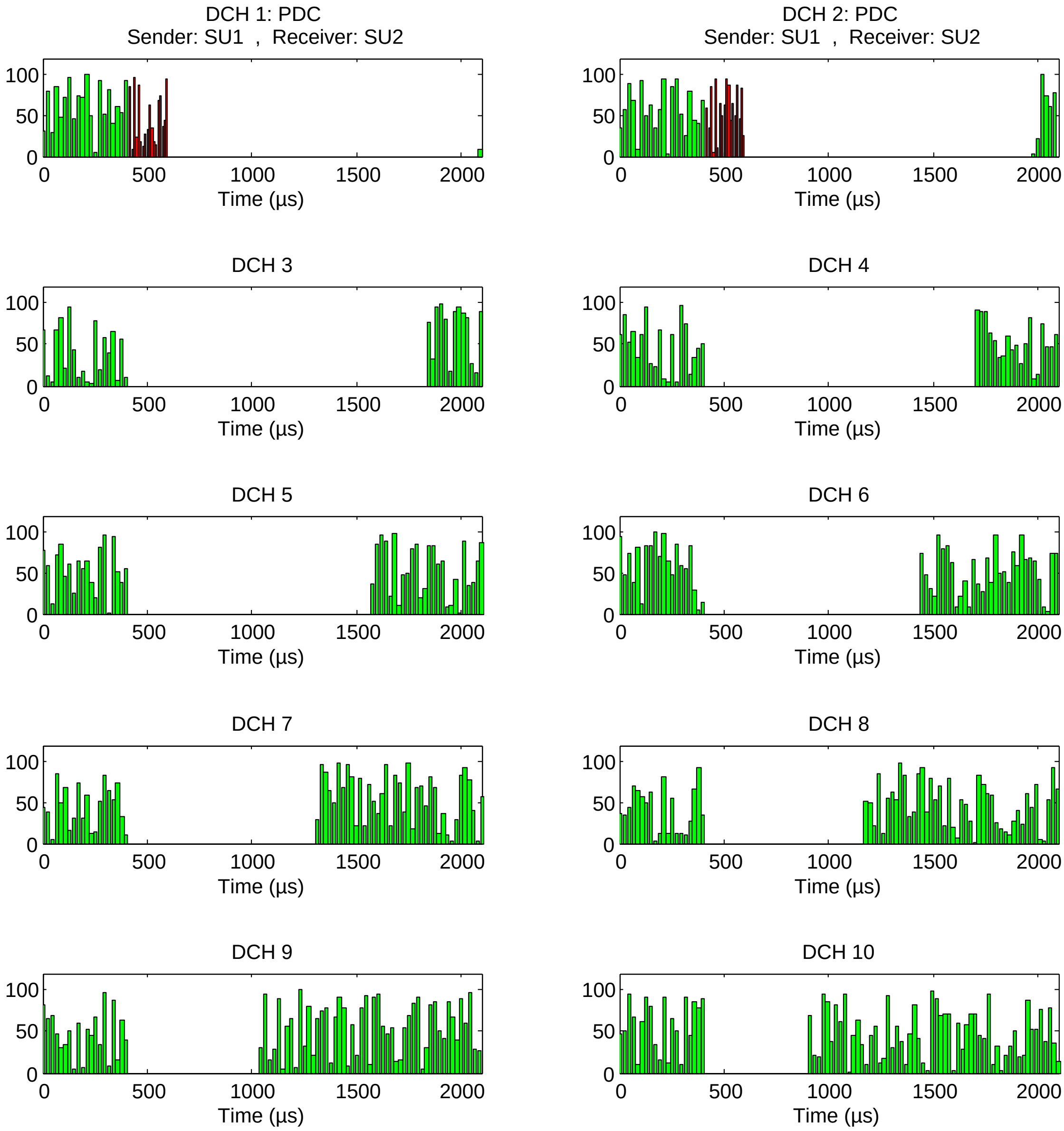

FIGURE 7.18: PUs activity over DCHs and SUs activity over DCHs 1 and 2

Figure 7.19 depicts the communication time and the energy consumed during the transmission of control and data information for the RECR-MAC protocol and the other benchmark CR-MAC protocols. The RECR-MAC protocol requires less time and transmitting energy to exchange their control and data information as compared to other CR-MAC protocols.

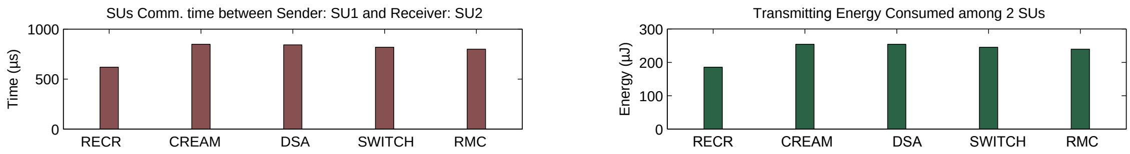

Figure 7.19: Communication time and transmitting energy consumed for CR-MAC protocols with 2 SUs

In Figure 7.20, the SUs exchange their control and data information over 10 DCHs and no PU activity is recorded during the exchange of data. The green lines indicate the PUs activity and red lines show SUs activities without overlapping each other so there is no interference. To avoid the interference among the PUs and SUs is one of the objectives of the proposed RECR-MAC protocol. The x-axis indicates the communicating time of the PUs and SUs over the control and data channels. The y-axis represents the PU and SU traffic in ASCII character format. Once the SUs successfully exchange their control information, they switch to DCHs, and then the rest of the SUs start exchanging their control information and make sure not to select the occupied DCHs. Due to the absence of interference among the PUs and SUs over DCHs, all sending SUs successfully received acknowledgment from receiving SUs. In the following figure, each SU pair exchange their data frames to their respective DCHs without interference to other SUs and PUs, showing that the hidden terminal and multi-channel hidden terminal problems have been well addressed.

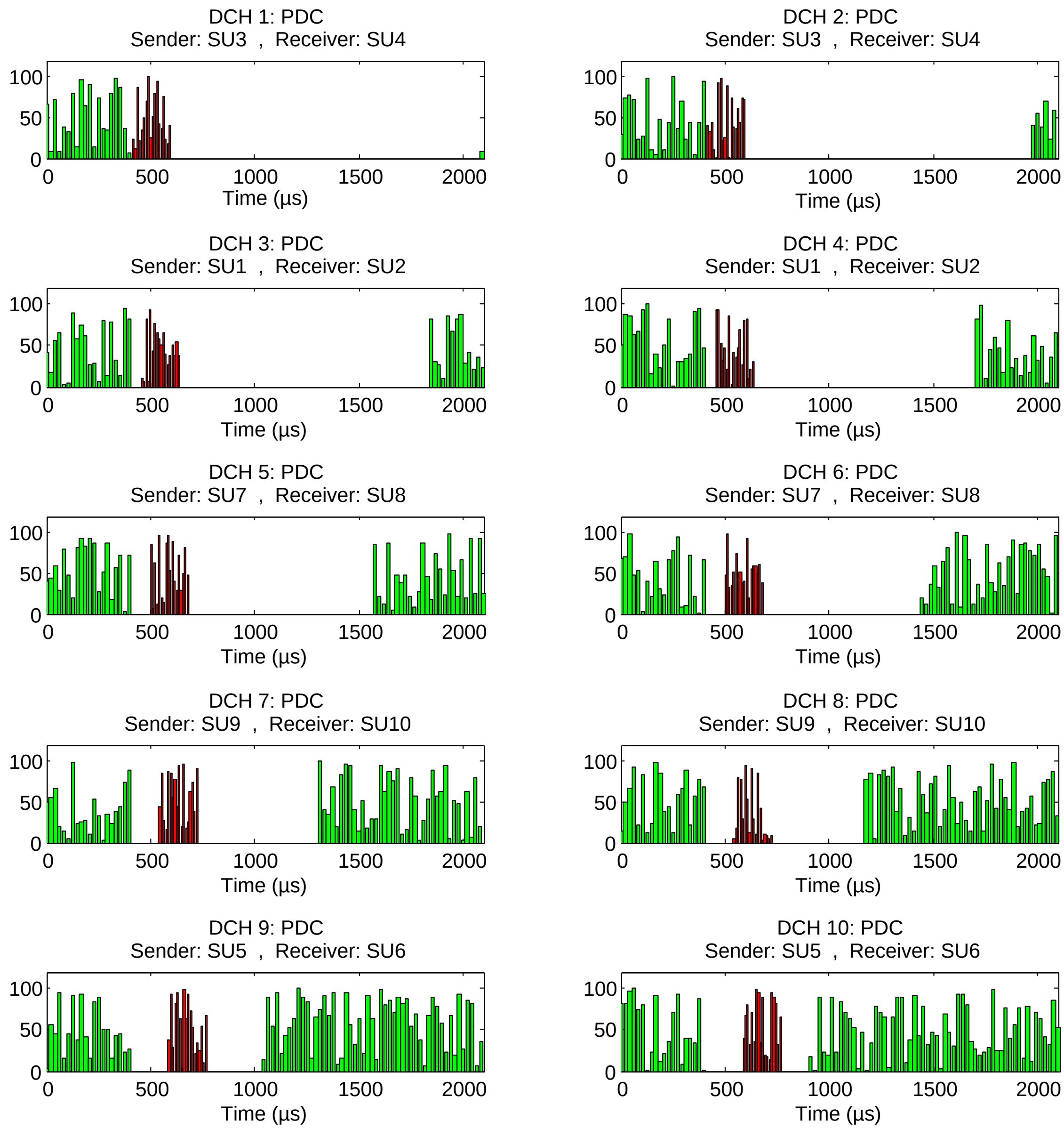

FIGURE 7.20: PUs and SUs activity over DCHs

Figure 7.21 depicts the comparison of communication time and transmitting energy over DCHs for the RECR-MAC protocol and benchmark CR-MAC protocols. The RECR-MAC protocol again shows that the SUs consume less communication time and transmitting energy over each pair of DCH as compared to the benchmark CR-MAC protocols [57] [20] [58] [23].

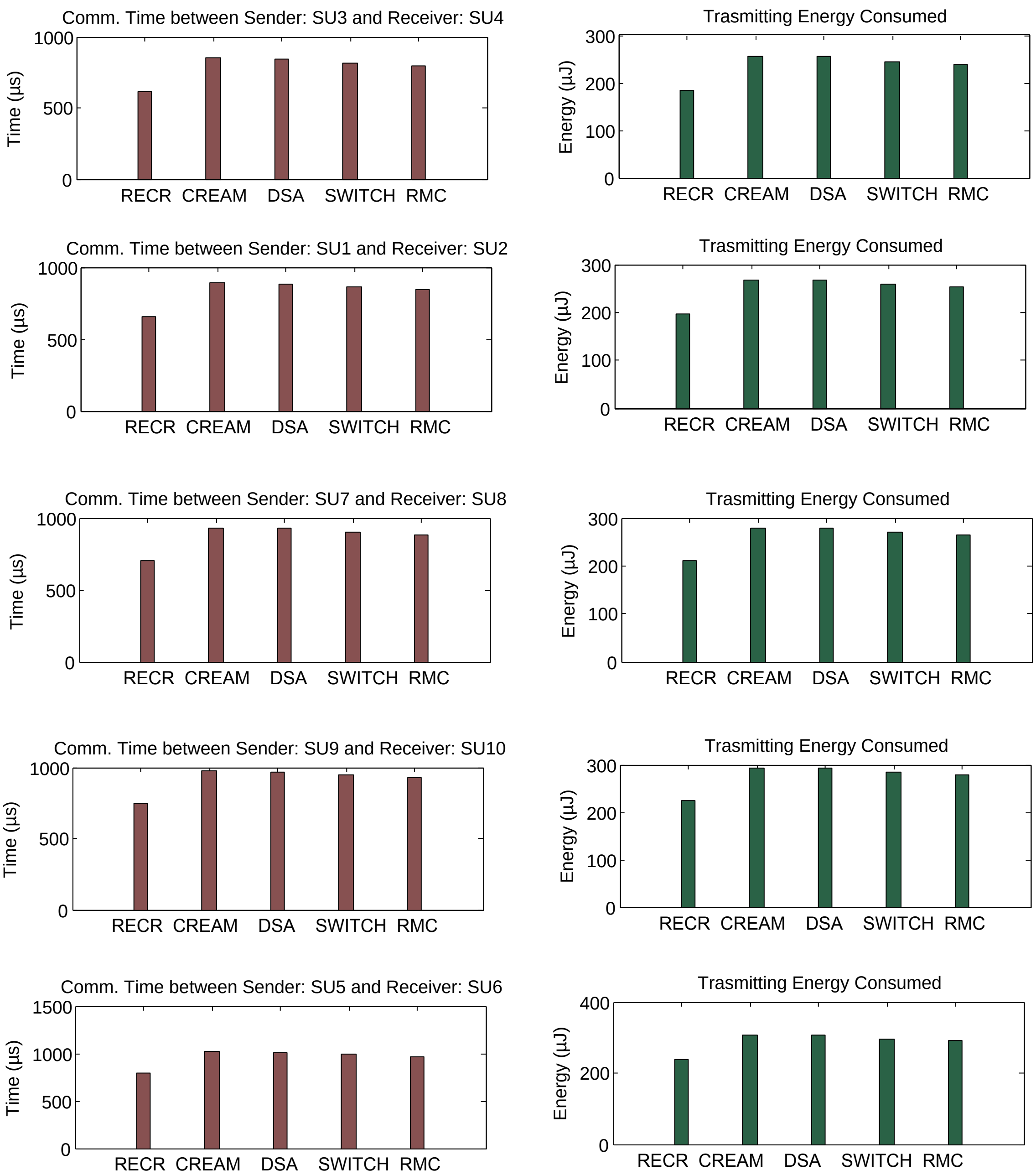

FIGURE 7.21: Communication time and transmitting energy for CR-MAC with 10 SUs

In Figure 7.22, it is worth noting that the performance of the RECR-MAC protocol shows enhanced performance with the increased number of SUs and DCHs due to its channel selection strategy. By adopting the same strategy and parameters used in the previous experiments, the RECR-MAC protocol achieves higher performance as compared to the benchmark CR-MAC protocols. The RECR-MAC protocol is capable to ensure the successful delivery of data over DCH with less communication time as compared to other CR-MAC protocols as depicted in Figure 7.22.

By considering 10 SUs, the RECR-MAC protocol saves approximately from 20% to 24% communication time as compared the other CR-MAC protocols. The x-axis shows the number of SUs increasing from 2 to 10, and the y-axis shows the communication time consumed for each pair of SU.

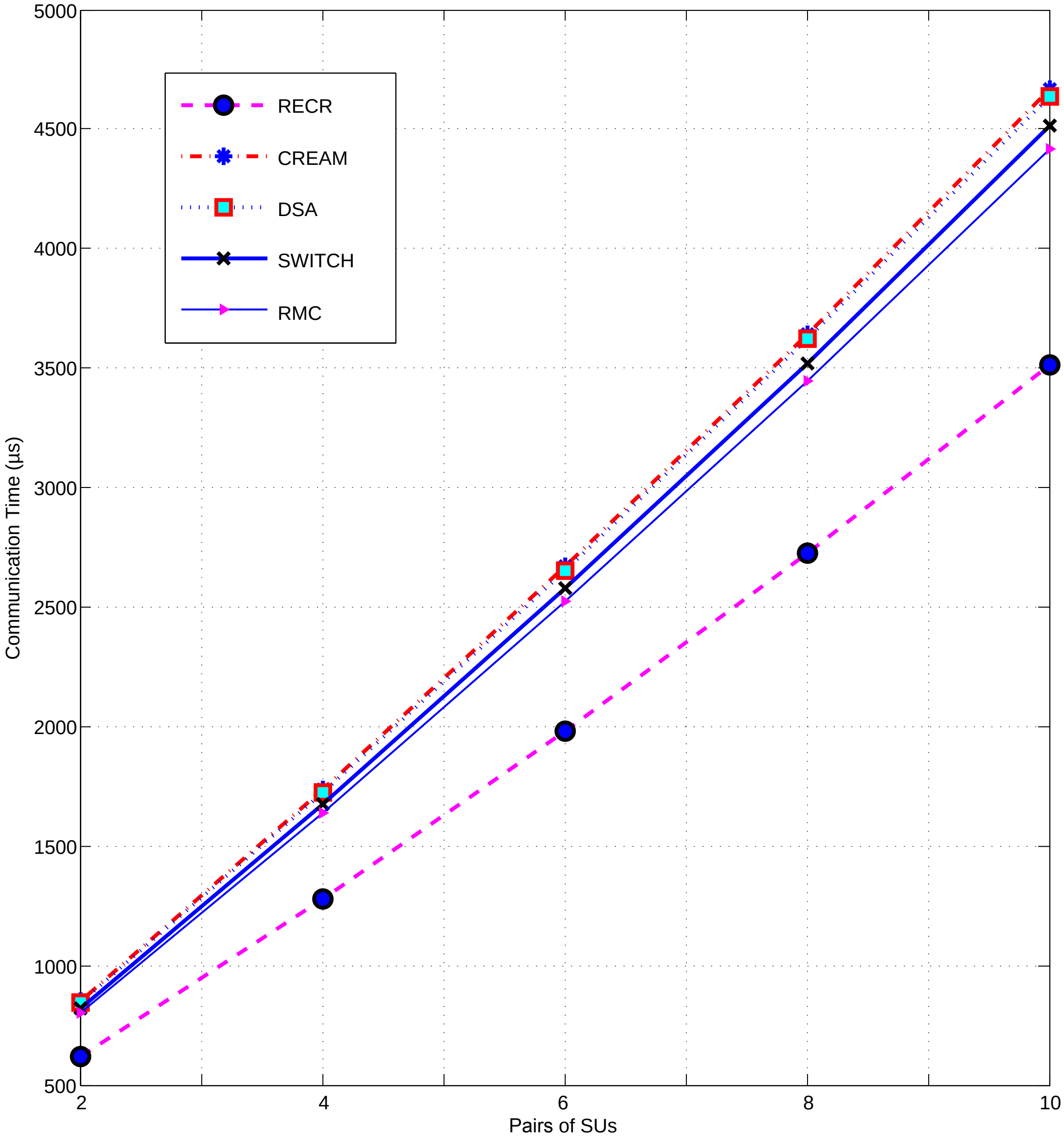

FIGURE 7.22: Communication time vs pairs of SUs of CR-MAC protocols

As mentioned above, the reduced communication time directly impacts the consumption of the transmitting energy among the SUs. Figure 7.23 illustrates that the RECR-MAC protocol requires less energy to successfully transmit their control and data information as compared to other CR-MAC protocols. The RECR-MAC protocol also saves 20% to 24% energy as compared to the other CR-MAC protocols by increasing the number of SUs. The y-axis represents the energy consumed by each protocol in this experiment. Saving energy is one of the major contributions during the designing of the RECR-MAC protocol, in case of PU returns or not, over the DCHs during the exchange of data frames among the SUs. Thus, the RECR-MAC protocol is capable to save more transmitting energy as compared to the benchmark CR-MAC protocols.

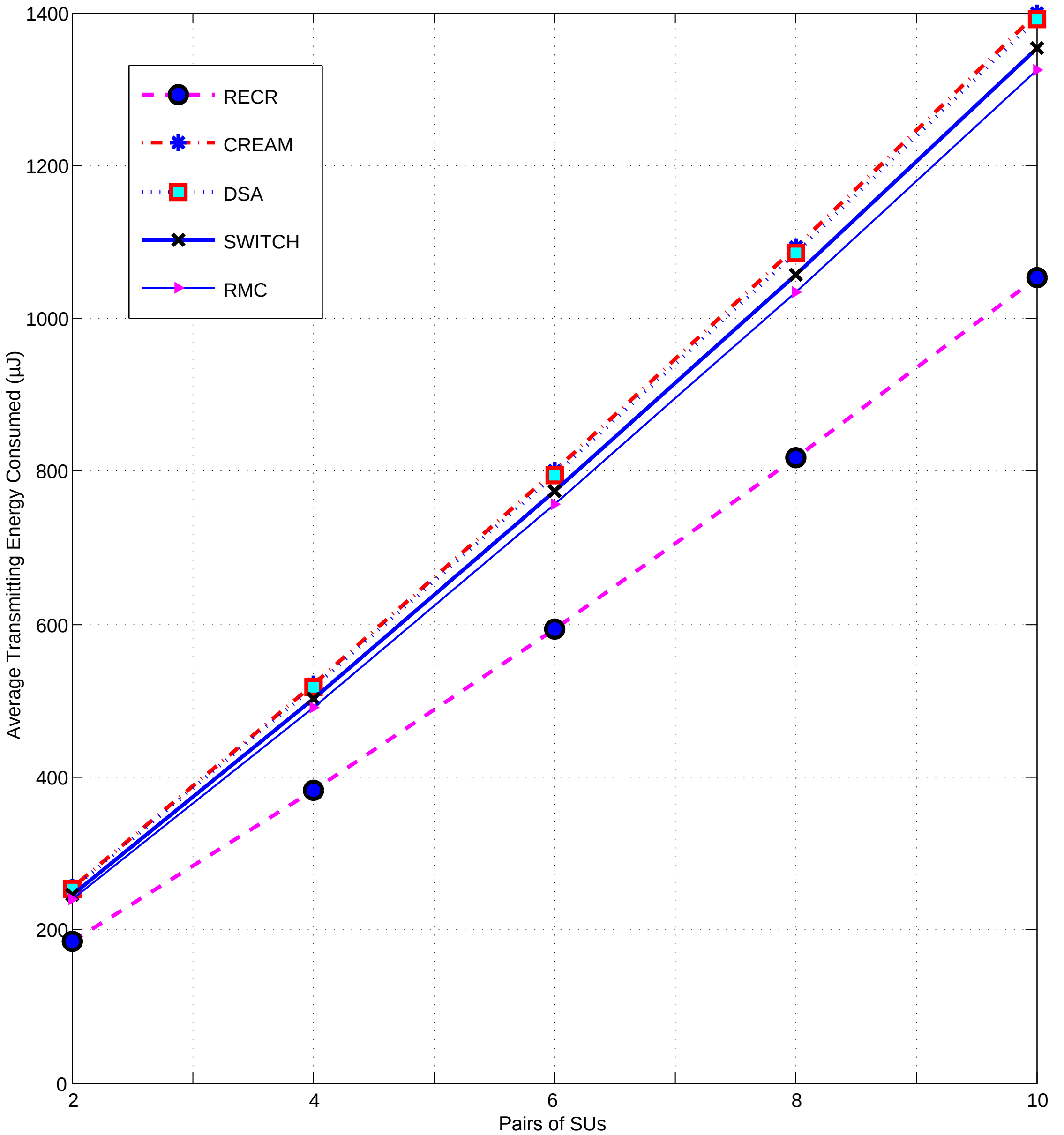

FIGURE 7.23: Transmitting energy consumed vs pairs of SUs of CR-MAC protocols

Table 7.7 shows the value of communication time and transmitting energy consumption during the sixth run of the simulation for RECR-MAC and other benchmark CR-MAC protocols. The following values indicate that the RECR-MAC protocol utilises less time and transmitting energy as compared to other CR-MAC protocols.

Table 7.7: Communication time and transmitting energy values utilised by 10 SUs without PU returns

	RECR	**CREAM**	**DSA**	**SWITCH**	**RMC**
Communication Time Utilised (s)	3514	4665	4636	4513	4419
Energy Transmitting (J)	1054	1399	1391	1354	1326

As discussed in Experiments 1 and 2, all CR-MAC protocols used two DCHs for simultaneous exchange of data information among SUs. However, in this experiment, all CR-MAC protocols communicate according to their design and characteristics. Figure 7.24 shows that the RECR-MAC protocol achieves higher throughput for a different number of SUs 2, 4, 6, 8 and 10 as compared to other benchmark CR-MAC protocols. The RECR-MAC protocol achieves more than double throughput under no PU returns is another contribution of this proposed protocol.

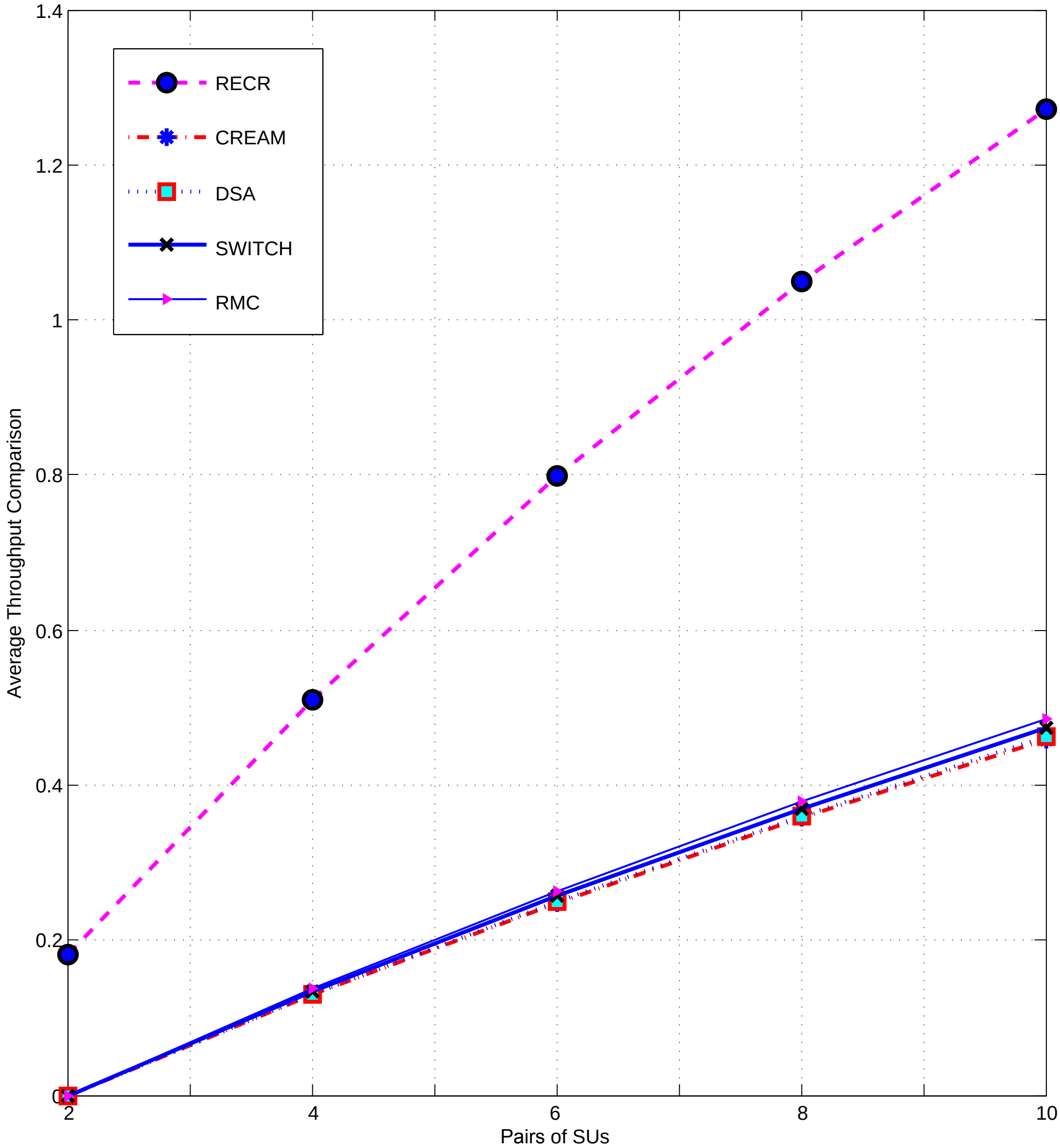

FIGURE 7.24: Average throughput comparison vs pairs of SUs of CR-MAC protocols

7.2.4 Experiment 4: Communication over DCHs with PU Returns

This experiment is also performed based on the parameters described in Tables 7.1 to 7.2 and Experiment 7.2.3, but PU returns during the 5th interval of the simulation over the DCH. The SUs are able to exchange any data size over the DCHs during the free time. However, the data size of 202 bytes is set for this experiment to validate the functionality of the RECR-MAC protocol. As discussed above, the RECR-MAC protocol selects the two most reliable DCHs for communication and the other benchmark CR-MAC protocols to start their control and data exchange process as discussed in [57] [20] [58] [23]. The simulation runs for six times, where the 1st run record the PUs activity and each of the following runs has 2, 4, 6, 8 and 10 SUs respectively. Figure 7.25 illustrates the PUs activity over the 10 DCHs with ON/OFF timings.

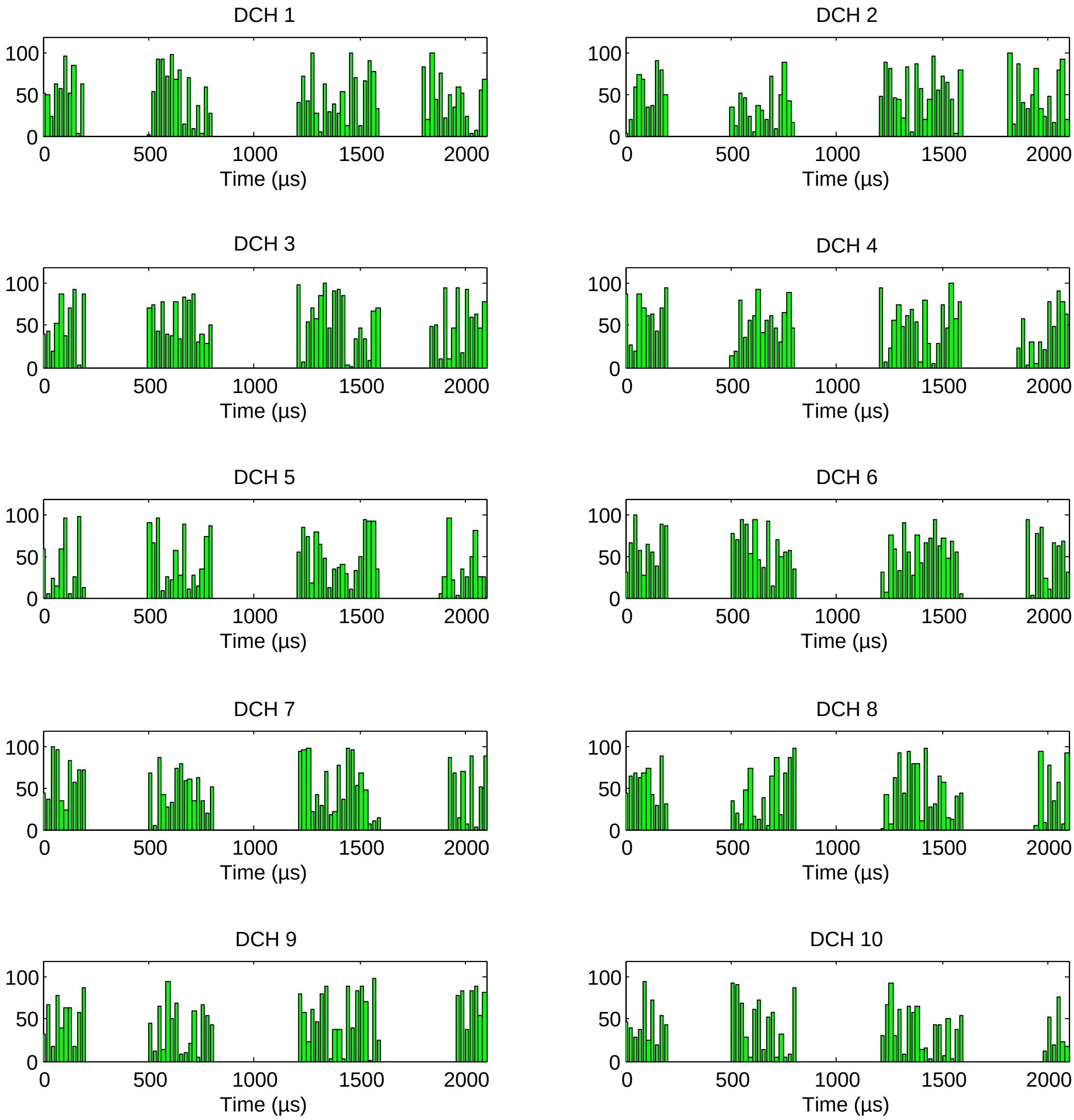

FIGURE 7.25: PUs activity over DCHs

During the 1st run of the simulation, the SUs record the PUs ON/OFF activities over DCHs and utilise these licensed DCHs without interference to the PUs. DCH 10 has a maximum available free time for SU; therefore, DCH 10 has high reliability in terms of available maximum free time and DCH 1 with least priority for data communication as compared the other available DCHs. During the 2nd run as shown in Figure 7.26, only a pair of SU is participating in communication over the two most reliable DCHs named as DCH 10 and DCH 9. The SUs 1 and 2 record the ON/OFF timings of the PUs over the licensed DCHs and immediately start their communication as soon as PU turns OFF. The results show the successful exchange of data among the SUs during the PUs OFF time. During the first gap over the DCHs 10 and 9, the SUs have got 202 bytes of data to transmit, but only 80 μs available after the exchange of control information. Therefore, the pair of SU is capable to hold the communication during the ON time of the PU and resume their data exchange when the next available free time starts from 800 μs. This validates the framework of the proposed RECR-MAC protocol.

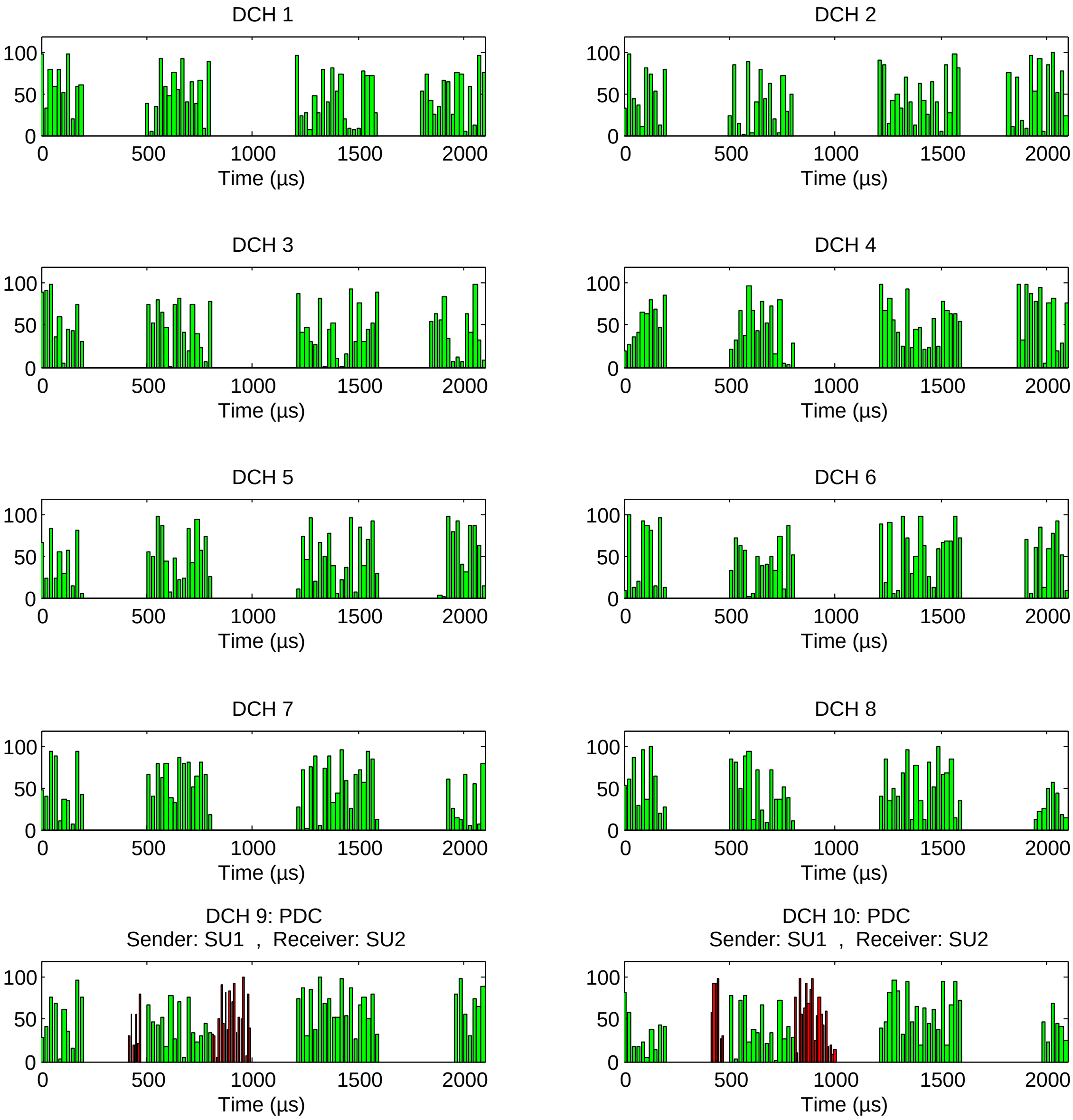

FIGURE 7.26: PUs activity over DCHs and SUs activity over DCHs 9 and 10

Figure 7.27 shows the communication time and energy consumed during the transmission of control and data frames by the RECR-MAC and other benchmark CR-MAC protocols. The RECR-MAC protocol requires less communication time and reduced transmitting energy to exchange the control and data information as compared to other selected benchmark CR-MAC protocols.

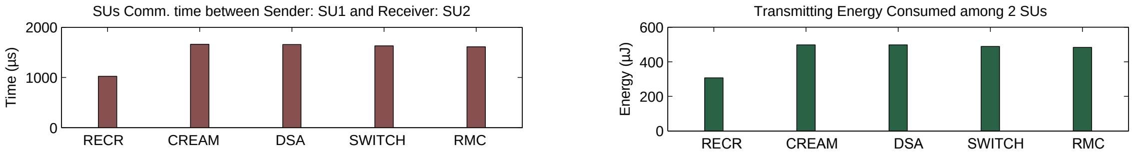

Figure 7.27: Communication time and transmitting energy consumed for CR-MAC protocols with 2 SUs

Figure 7.28 shows the activities of SUs and PUs over the DCHs. Instead of PU returns during the data communication, the PUs are occupying DCHs 1 and 9 during the entire time and do not leave any time for SUs communication over these DCHs. The RECR-MAC protocol is capable to handle this critical situation and switch to DCHs 2 and 10, named BDCs to exchange their data frames among the SUs with no interference to the PUs. The other SUs exchange their data over their respective DCHs named as PDCs and no PU returns are recorded over these DCHs.

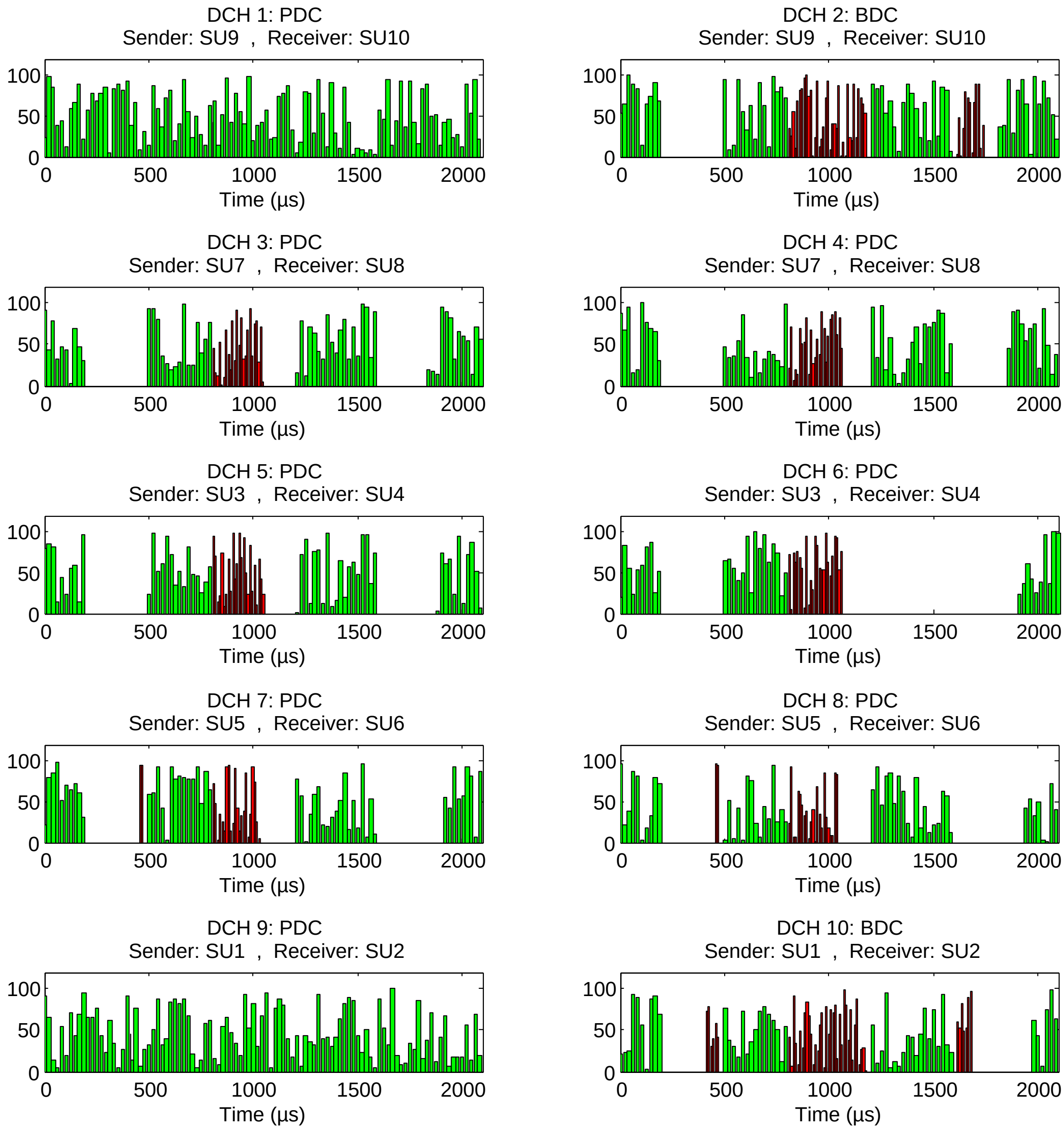

FIGURE 7.28: PUs and SUs activity over DCHs

The DCHs 9 and 1 have been occupied by the PUs all the time and SUs have only transferred their data over their BDCs such as DCHs 10 and 2 as shown in Figure 7.28. Therefore, the RECR-MAC protocol is able to manage PU returns, no PU returns and PU occupied the DCHs all the times. Thus, the RECR-MAC protocol saves additional time and transmitting energy with PU returns which is another contribution of this thesis. In general, if PU returns during the communication, the SUs re-start their entire operation, as discussed in CREAM-MAC and DSA-MAC, instead of switching to the BDCs. However, the SWITCH-MAC and RMC-MAC protocols are capable to handle the situation when PU returns, but they require additional time and transmitting energy to accomplish their communication as compared to the RECR-MAC protocol due to additional overheads over control and data channels. The usage of communication time and transmitting energy between RECR-MAC and benchmark CR-MAC protocols can be observed in Figure 7.29.

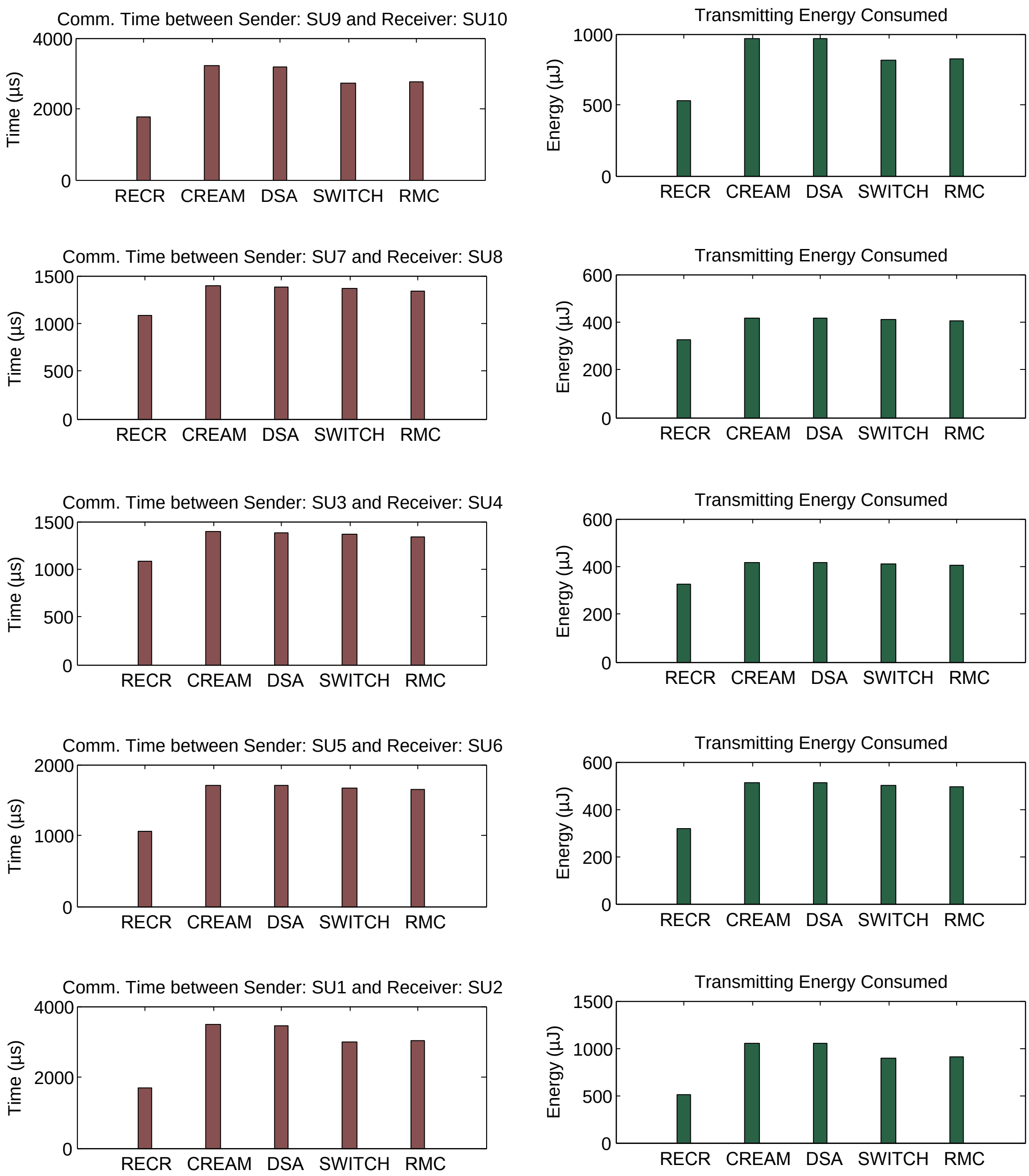

FIGURE 7.29: Communication time and transmitting energy for CR-MAC with 10 SUs

In Figure 7.30, it is also worth noting that with the increasing number of SUs and DCHs, the RECR-MAC protocol shows enhanced performance even though the PU returns over DCHs 1 and 9. The RECR-MAC protocol is capable to ensure the successful delivery of the data over the DCHs with less communication time as compared to other benchmark CR-MAC protocols. Furthermore, it saves additional time and transmitting energy with PU returns. To conclude, the RECR-MAC protocol saves approximately from 33% to 40% communication time as compared the other benchmark CR-MAC protocols. The x-axis shows the number of SUs increase from 2 to 10, and the y-axis shows the communication time consumed by each pair of SU.

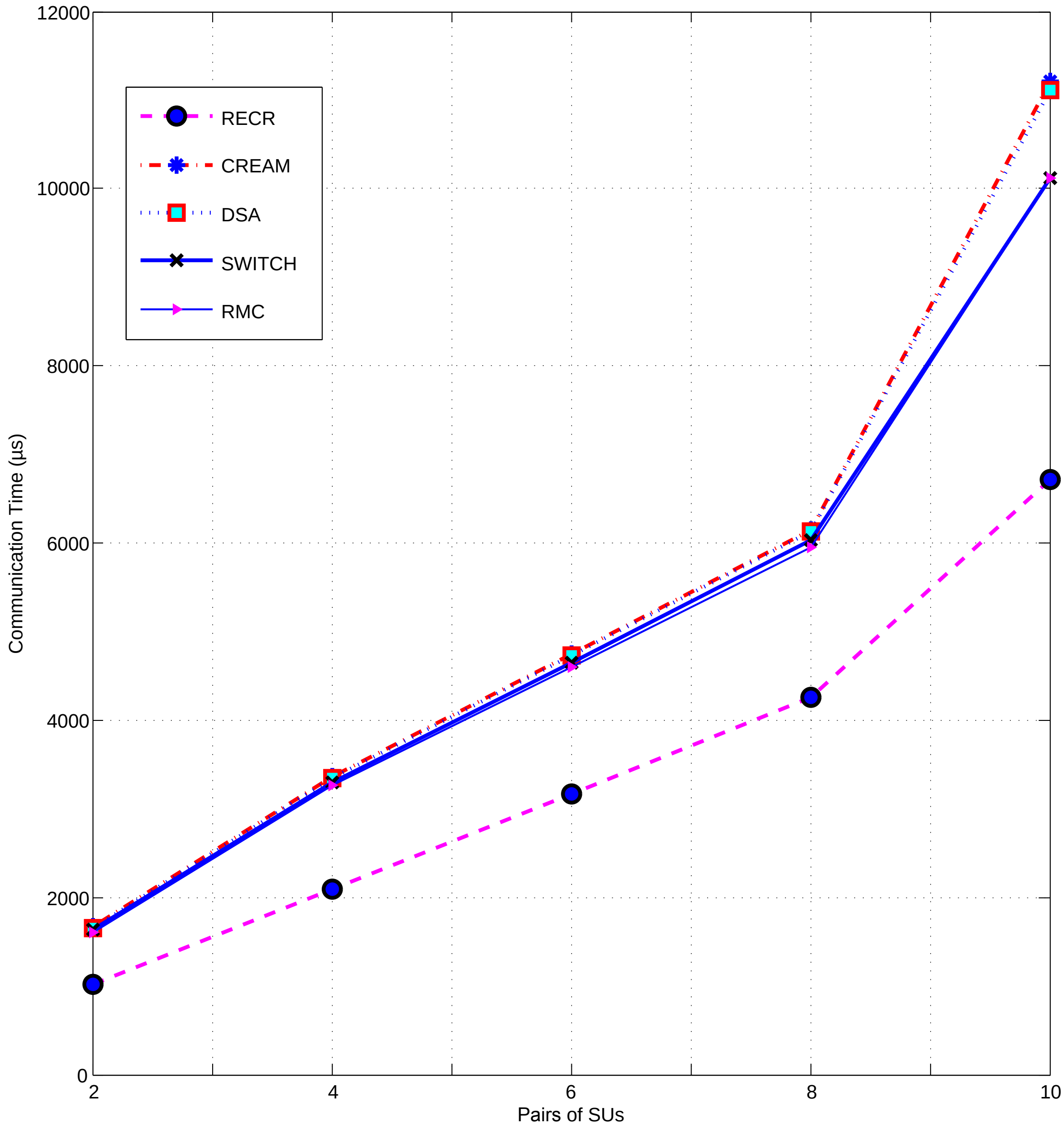

FIGURE 7.30: Communication time vs pairs of SUs of CR-MAC protocols

Figure 7.31 shows that the RECR-MAC protocol requires less transmitting energy to successfully transmit its control and data frames as compared to other benchmark CR-MAC protocols. In this experiment, the RECR-MAC protocol saves 33% to 40% transmitting energy as compared to the other benchmark CR-MAC protocols by increasing the number of SUs as shown on the x-axis. The y-axis represents the transmitting energy by each protocol mentioned in this experiment. Saving energy is one of the major contributions to the design of the RECR-MAC protocol especially when the PU returns frequently.

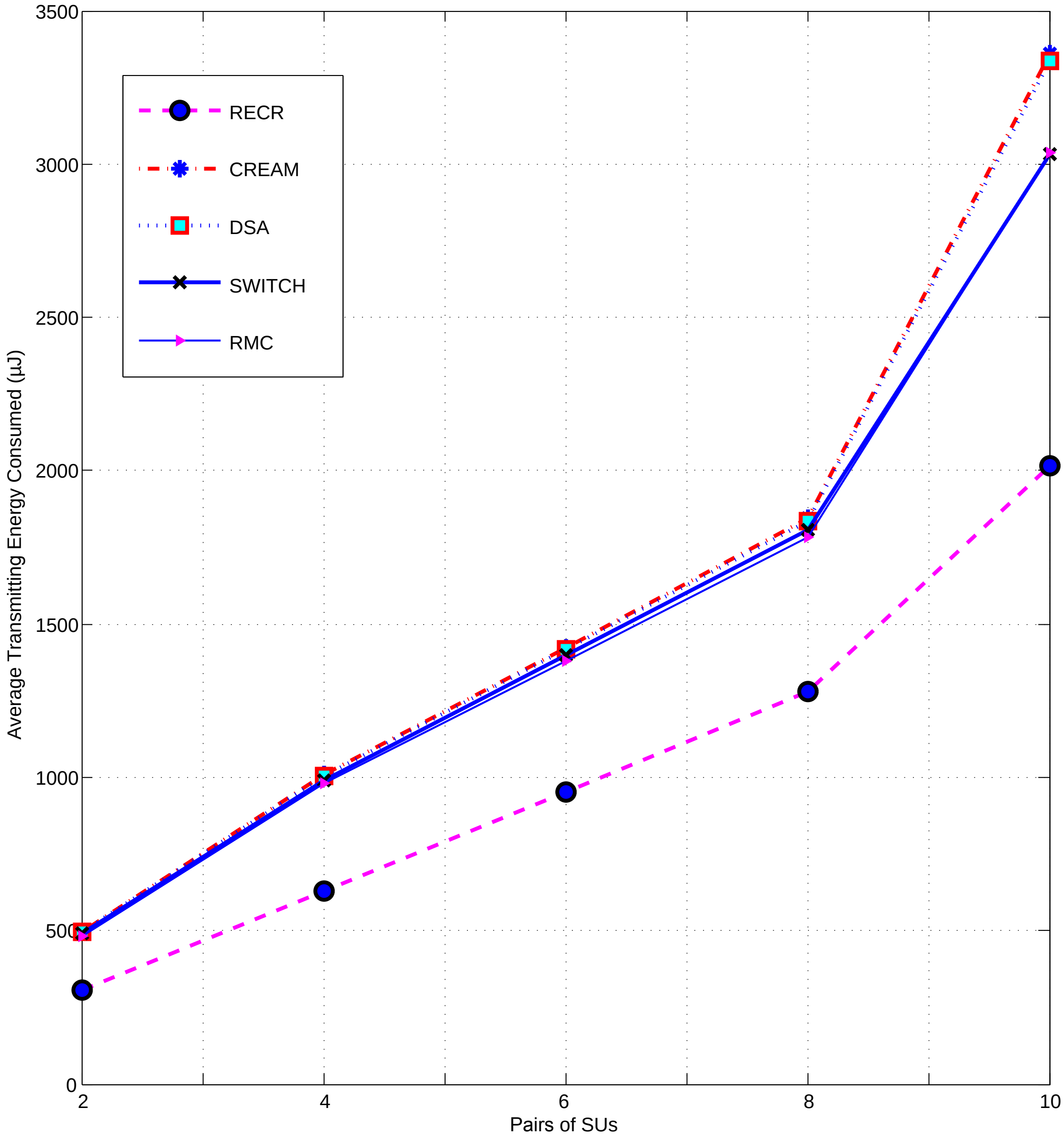

Figure 7.31: Transmitting energy consumed vs pairs of SUs of CR-MAC protocols

Table 7.8 shows the value of communication time and transmitting energy consumption during the final (6th) run of the simulation for RECR-MAC and other CR-MAC protocols. The values clearly indicate that the RECR-MAC protocol utilises less communication time and reduces transmitting energy as compared to other CR-MAC protocols.

TABLE 7.8: Time and Energy values utilised by 10 SUs with frequent PU returns

	RECR	**CREAM**	**DSA**	**SWITCH**	**RMC**
Time Utilised (ms)	6.717	11.2	11.12	10.12	10.11
Energy Transmitting (mJ)	2.015	3.361	3.336	3.036	2.015

As discussed in Experiments 7.2.1 and 7.2.2, all CR-MAC protocols used two DCHs for simultaneous transmission of data among SUs. However, in this experiment, all CR-MAC protocols are exchanging control and data frames according to their design as discussed in [57] [20] [58] [23]. The throughput is investigated for a different number of SUs 2, 4, 6, 8 and 10 in this simulation to make the model more robust. The RECR-MAC protocol achieves three times more throughput with PU returns as compared to the benchmark CR-MAC protocols, another achievement of the proposed RECR-MAC protocol as shown in Figure 7.32.

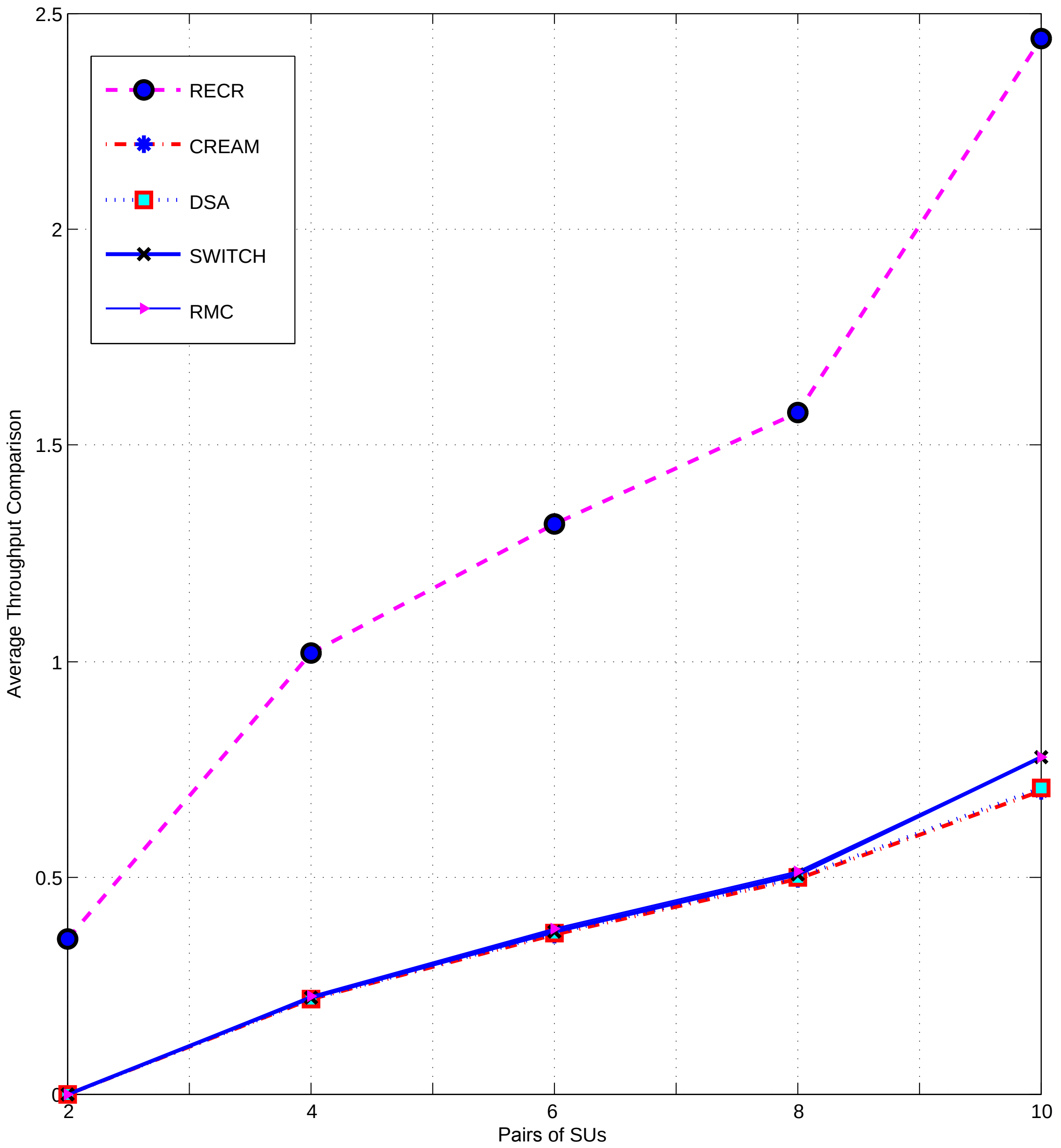

FIGURE 7.32: Average throughput comparison vs pairs of SUs of CR-MAC protocols

7.2.5 Experiment 5: Communication over DCHs with and without PU Returns

In this simulation based experiment, multiple cases are discussed to validate the performance of the RECR-MAC protocol, without and with PU returns during the data communication, and with PU occupying the DCH 5 for the entire 2100 μs during the 4th run of the simulation. This experiment utilises the same parameters as used in Experiment 7.2.4 but the PU ON/OFF timing is increased. The time slots are divided into small parts to test the stability of the RECR-MAC protocol and its ability to handle the multiple situations in the CRAHNs. During the initialization of the network, the PUs exchange their communication over their licensed DCHs, then during the 2nd and 3rd run, SUs exchange their control and data frames without any PU returns. During the 4th run of the simulation, the PUs turn ON during the entire 2100 μs over DCHs 2 and 5. During the 5th run, PU returns over DCH 8 during the communication and PU also returns over DCH 10 during the 6th and final run of the simulation. Figure 7.33 illustrates the activity of the PUs over the DCHs including ON/OFF timings. The SUs record the free time during the PUs activity and prepare their transceivers to effectively utilise the available free time without any interference, especially when the gaps among the PUs traffic are smaller in size as compared to those discussed in Experiments 1 to 4.

FIGURE 7.33: PUs activity over DCHs

Table 7.9 shows the ranking of each DCH after the initialisation of the CR network. As discussed in Chapter 4, DCH 10 has high rank as compared to other DCHs.

TABLE 7.9: Ranking of DCHs after initialisation of the network with available time (μs)

DCH1	**DCH2**	**DCH3**	**DCH4**	**DCH5**	**DCH6**	**DCH7**	**DCH8**	**DCH9**	**DCH10**
966	984	1004	1023	1043	1062	1088	1107	1127	1146
Rank10	Rank9	Rank8	Rank7	Rank6	Rank5	Rank4	Rank3	Rank2	Rank1

During the 2nd run of the simulation, the SUs 1 and 2 select DCHs 10 and 9 for their data communication after a successful exchange of control frames as shown in Figure 7.34. It is observed that the data communication should start from 418 μs but it starts after 601 μs because the licensed DCHs 10 and 9 have been occupied by the PUs during the period from 400 to 600 μs. The SUs 1 and 2 start their data communication from 601 μs which proves the reliability and sensing ability of the RECR-MAC protocol. In addition, the PUs turn ON again at 800 μs, and then the SUs immediately stop their communication to avoid any interference with the PUs traffic, which shows another cognitive capability of the proposed RECR-MAC protocol.

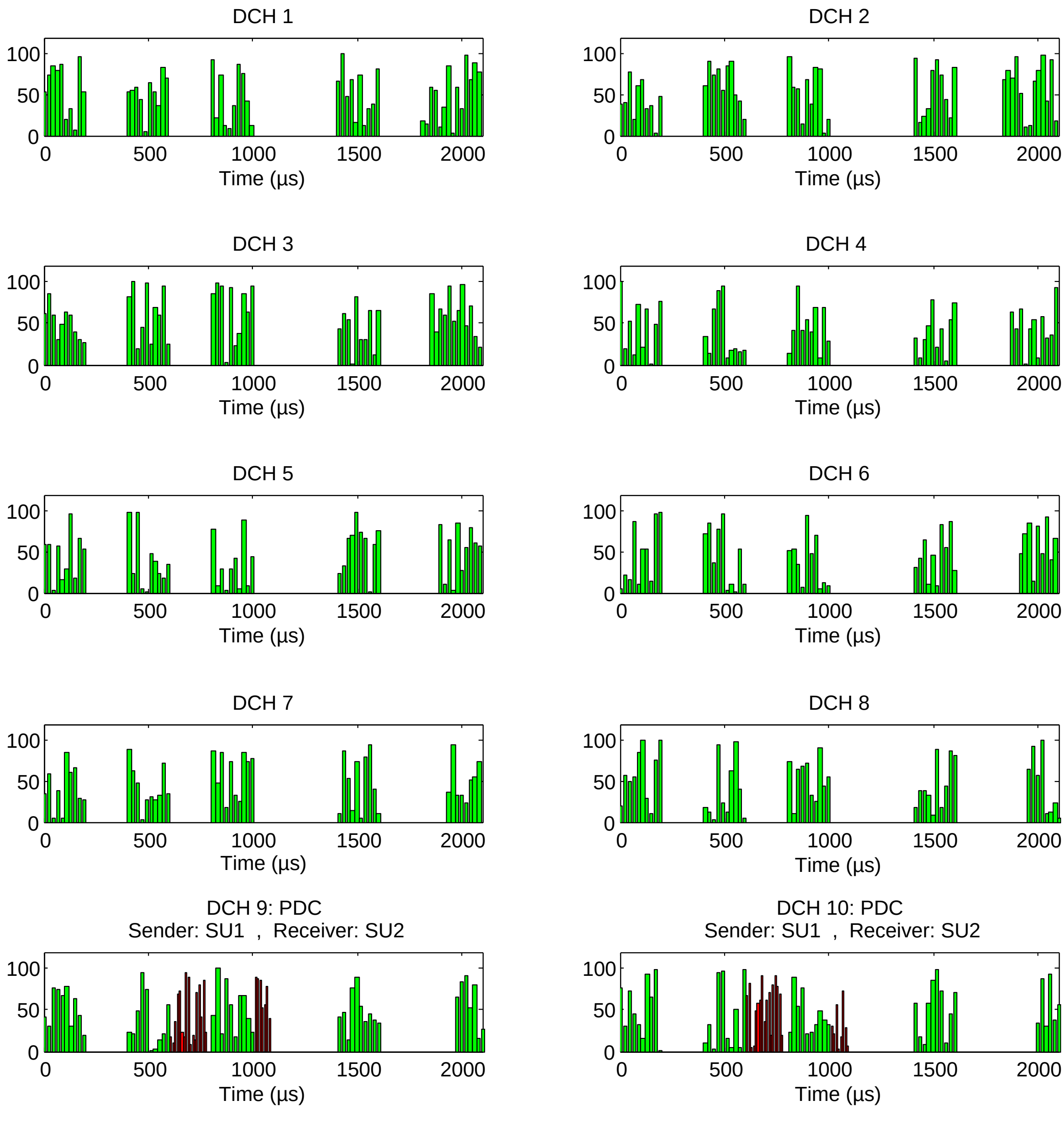

FIGURE 7.34: PUs activity over DCHs and SUs activity over DCHs 9 and 10

During the 2nd run of the simulation, SUs 1 and 2 successfully exchange their control and data frames as shown in Figure 7.34. The RECR-MAC protocol requires less communication time and transmitting energy between two SUs exchanging its control and data frames as compared to other benchmark CR-MAC protocols as shown in Figure 7.35.

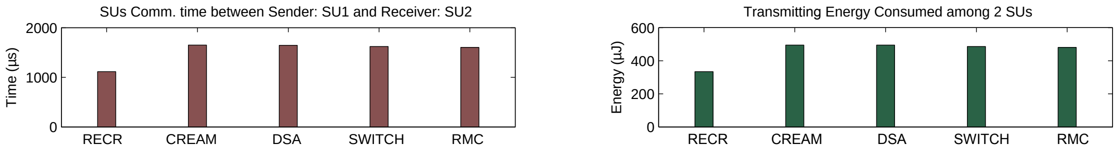

Figure 7.35: Communication time and transmitting energy consumed for CR-MAC protocols with 2 SUs

During the 3rd run of the simulation, four SUs participate and successfully acknowledge their control and data frames. In addition, During the 4th simulation run, six SUs participate and DCHs 2 and 5 are occupied by the PUs all the time. The SUs 1 and 2 select DCHs 7 and 8, SUs 3 and 4 select DCHs 9 and 10, and SUs 5 and 6 select DCHs 5 and 6 for their data communication. However, DCHs 2 and 5 are occupied by PUs during this run. Therefore, these DCHs, 2 and 5, have low reliability as compared to other available DCHs based on the Equations 4.1. SUs 1 to 4 transmit and receive their data without any interference, but SUs 5 and 6 are only able to transmit their entire data over DCH 6 as a BDC because DCH 5 has no free time for SUs as shown in Figure 7.36.

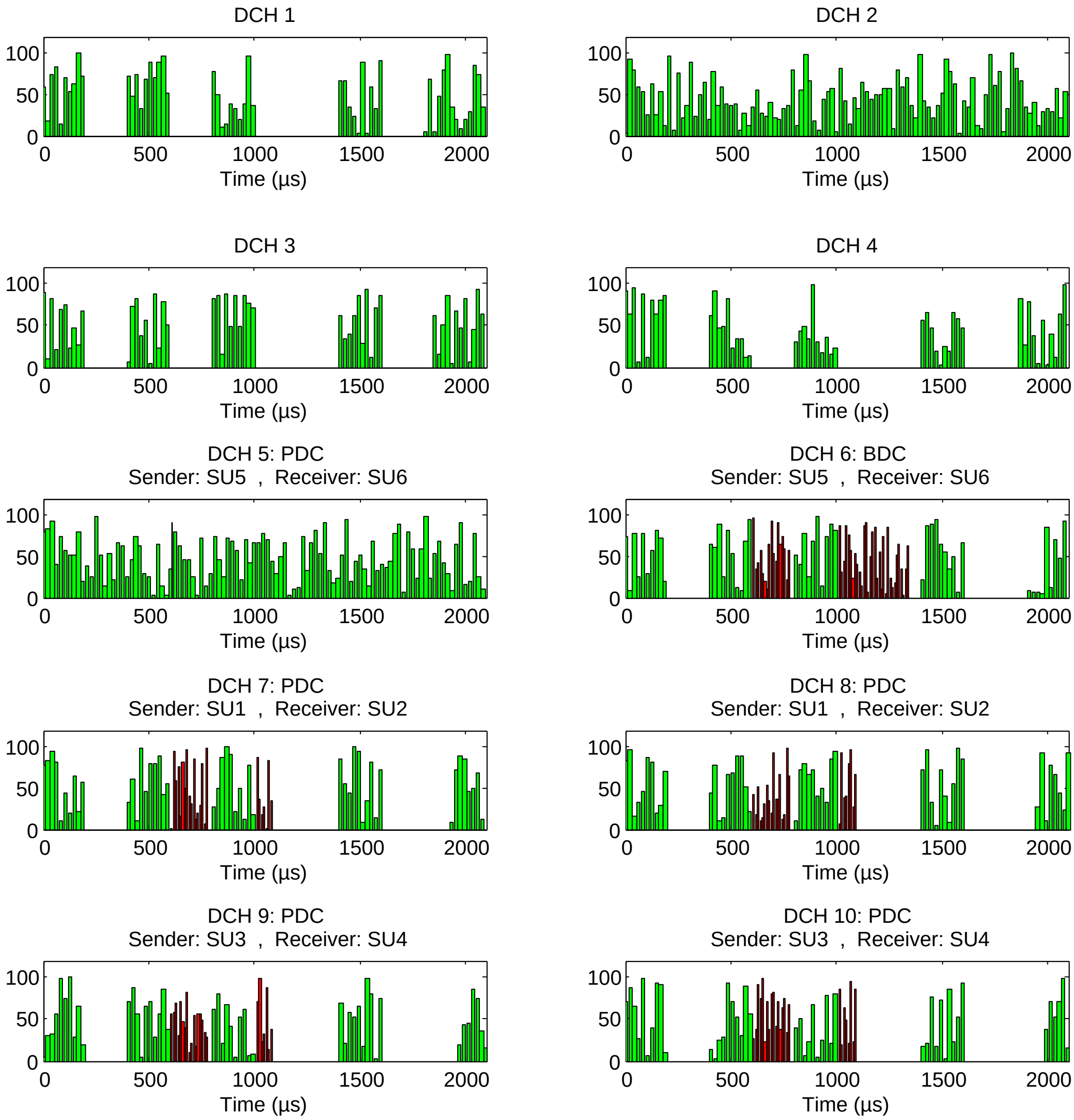

FIGURE 7.36: PUs activity over DCHs and SUs activity over DCHs 6 to 10

During the 4th run, SUs 1 to 6 successfully exchange their control and data information as shown in Figure 7.37, where PU occupied the DCH 5 for the entire duration. The RECR-MAC protocol requires less time and transmitting energy to exchange its control and data frames as compared to other benchmark CR-MAC protocols.

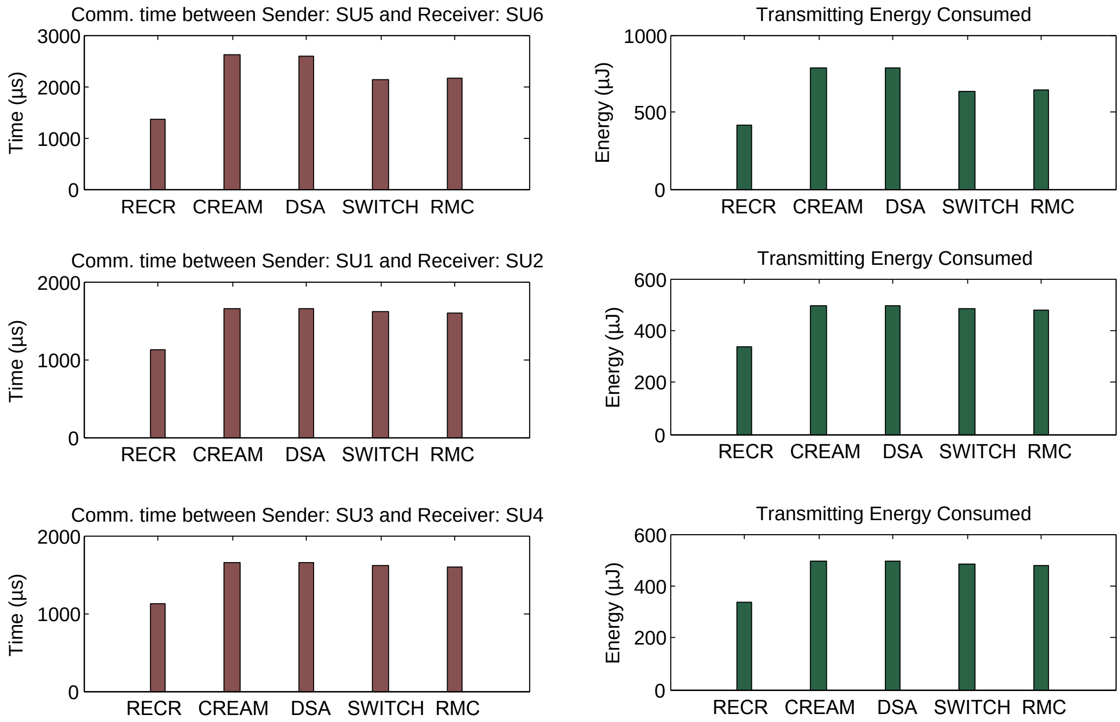

FIGURE 7.37: Time and transmitting energy consumed for CR-MAC protocols with 6 SUs

During the 5th run of this experiment, eight SUs participate and successfully acknowledge their control and data frames. Over the DCH 8, the PU starts its activity from 0 to 200 μs and re-starts from 1941 to 2100 μs. The SUs record the maximum duration of OFF period, 201 to 1940 μs, over the DCH 8 as compared to the other DCHs, which increases the channel reliability for the next pair of SUs during the following run. The SUs 1 and 2 take the opportunity and exchange their data with successful acknowledgment. The SUs 1 to 4 transmit and receive their data frames without any interference, but SUs 5 and 6 transmit their entire data over the DCH 6, as a BDC, because DCH 5 was occupied by the PUs during the entire time as shown in Figure 7.36. The DCHs 2 and 5 are not selected for this run because of two reasons; a) both DCHs were entire busy during the 4th run and b) only four pairs of SU participate during the 5th run, so DCHs 2 and 5 have least ranking as compared to the other available DCHs based on the previous run. Thus, all participating SUs successfully exchanged their control and data frames as shown in Figure 7.38. The activities of the SUs over the DCHs 1, 3, 4, 6, 7, 8, 9, 10 show the validity of the RECR-MAC protocol framework.

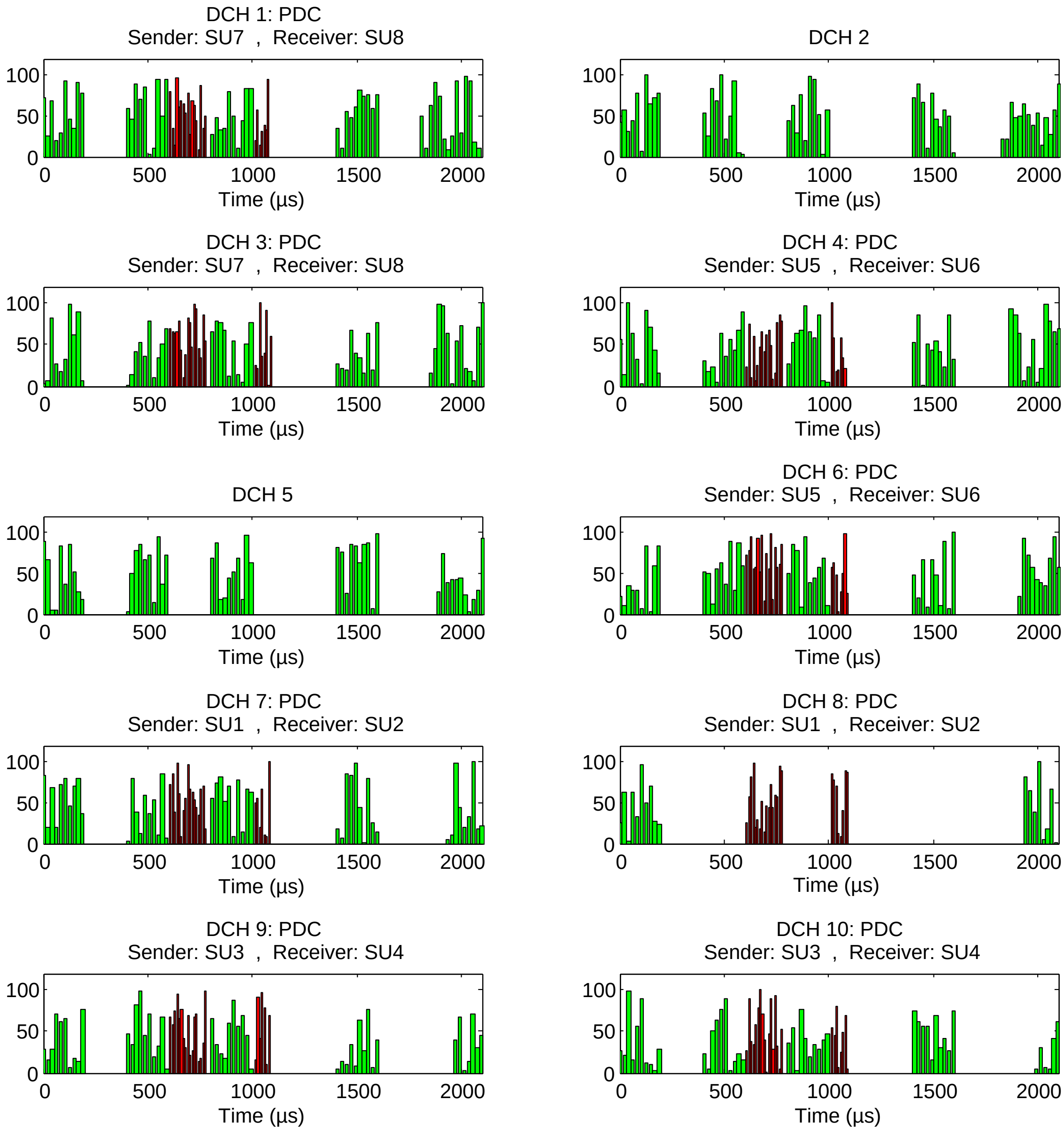

Figure 7.38: PUs and SUs activity over DCHs with PU returns

To conclude, during the 5th run of this experiment, SUs 1 to 8 successfully exchange their control and data frames as depicted in Figure 7.38. The RECR-MAC protocol requires less time and transmitting energy to exchange its control and data frames as compared to other benchmark CR-MAC protocols as shown in Figure 7.39.

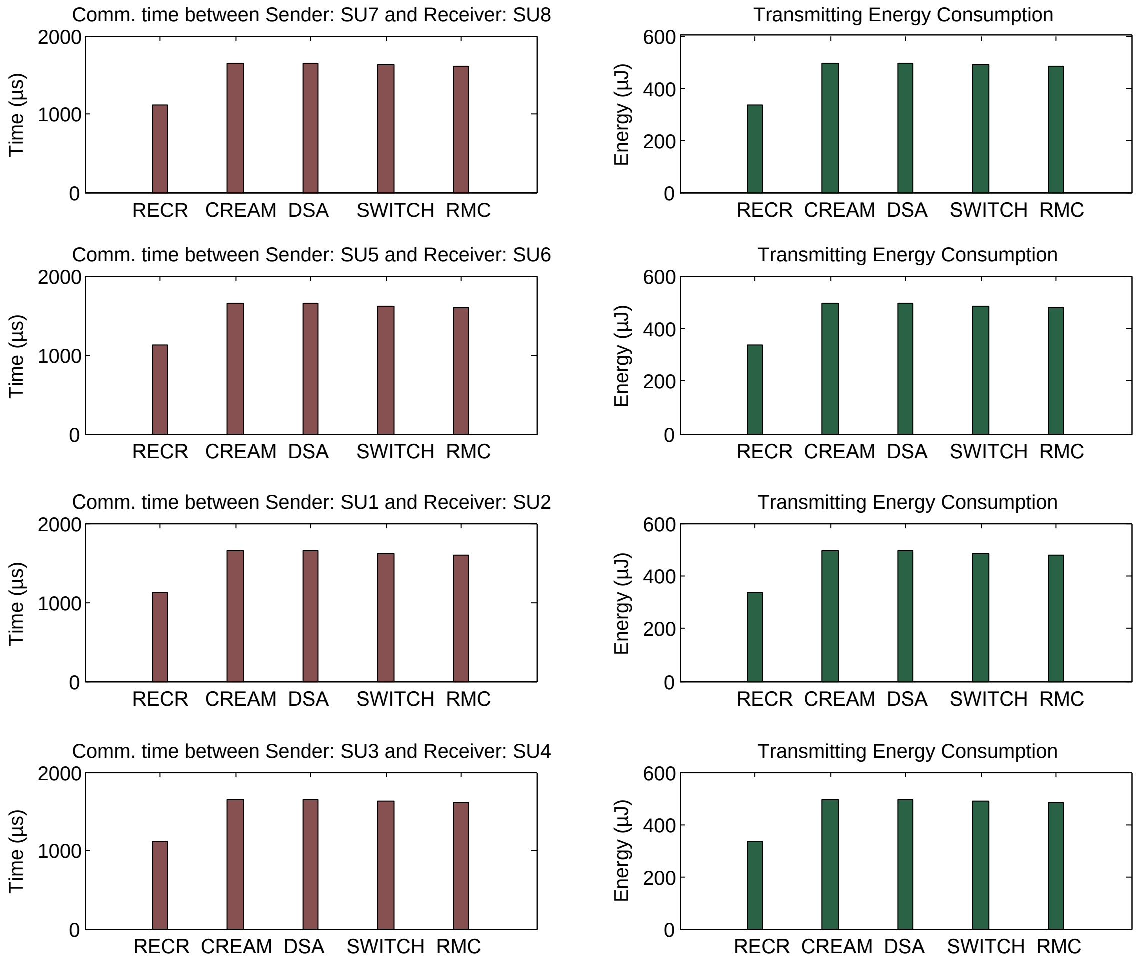

FIGURE 7.39: Communication time and transmitting energy consumed for CR-MAC protocols with 8 SUs

During the 6th (final) run of this experiment, ten SUs participate to exchange their control and data frames. Based on the channel ranking criteria, the DCH 8 has lowest ranking in this network and SUs 5 and 6 are unable to use this channel as a PDC; therefore, both SUs 5 and 6 transmit their entire data over the DCH 1. In addition, PU returns over DCH 10 during the communication of SUs 1 and 2; therefore, SUs 1 and 2 re-transmit their entire data over the DCH 9, as a BDC, and receive successful acknowledgment. The rest of the SUs select their respective DCHs and communicate accordingly. Therefore, all participating SUs successfully exchange their control and data information as shown in Figure 7.40. Such distributed activities of the PUs and SUs provide another example of the RECR-MAC protocol capability to handle other critical situations which shows the reliability of the protocol.

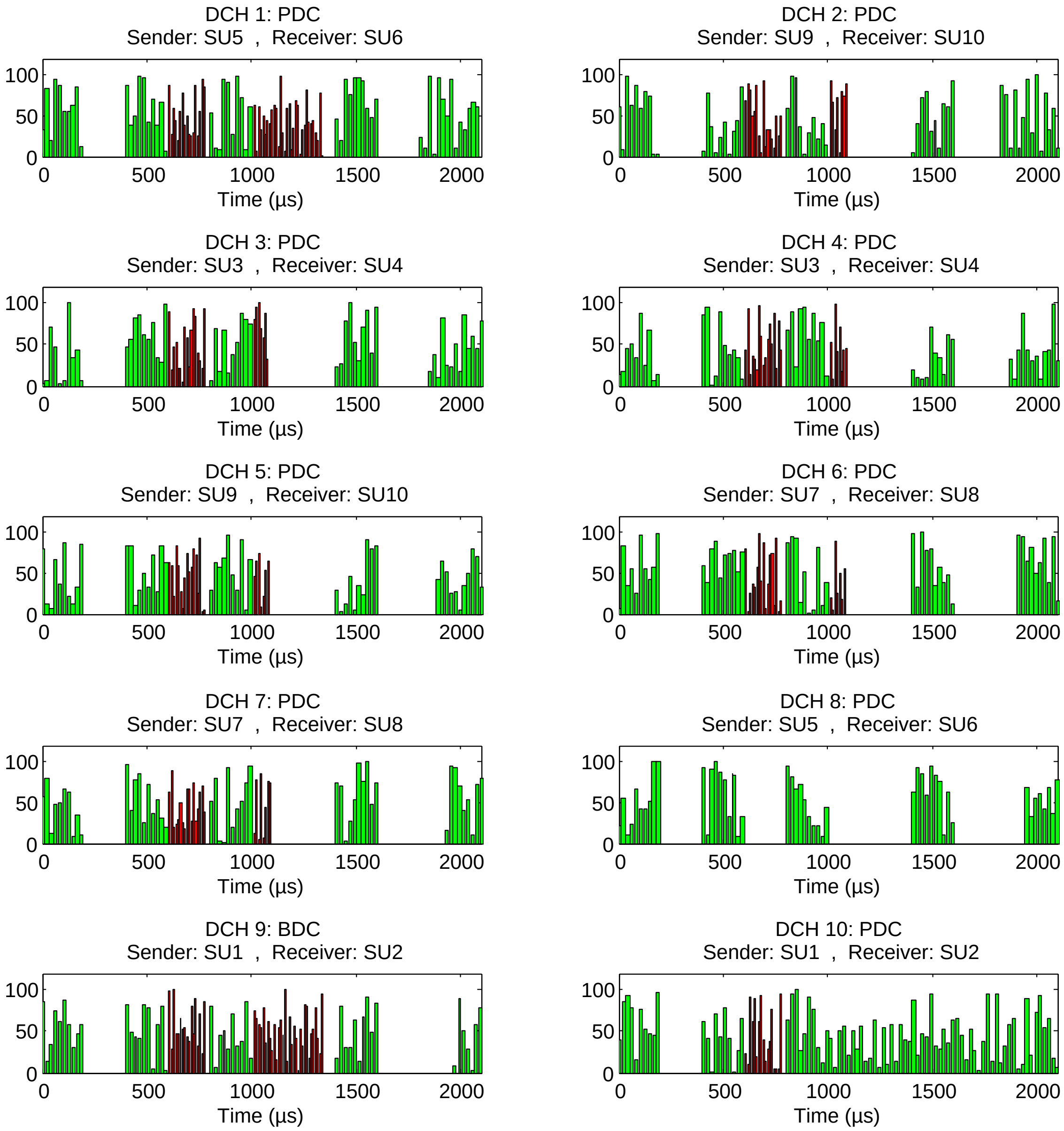

FIGURE 7.40: PUs and SUs activity over the DCHs with PU returns

To conclude, during the 6th run of this experiment, SUs 1 to 10 successfully exchange their control and data frames as depicted in Figure 7.41. The RECR-MAC protocol requires less communication time and transmitting energy to exchange its control and data frames as compared to the benchmark CR-MAC protocols.

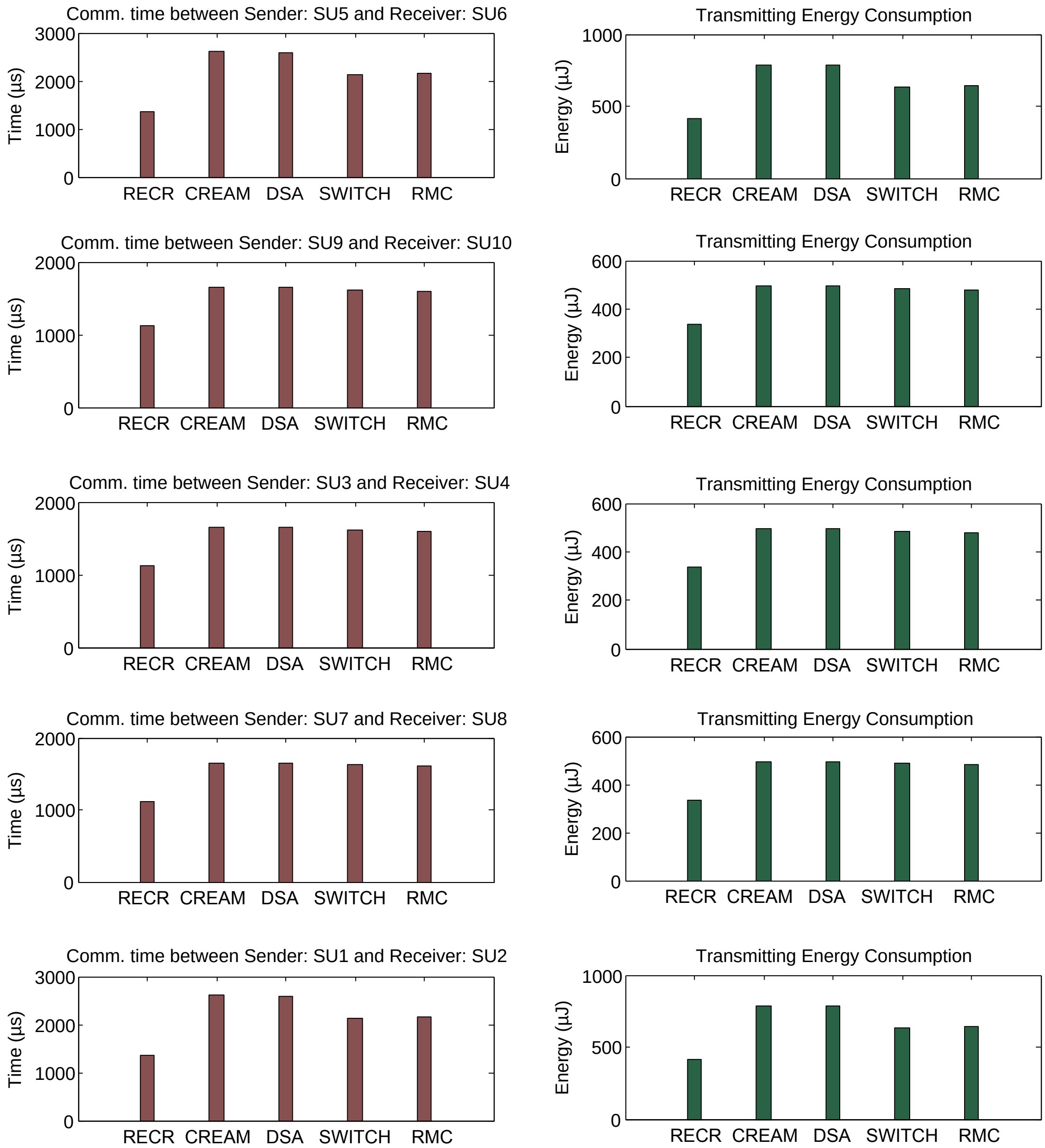

Figure 7.41: Communication time and transmitting energy consumed for CR-MAC protocols with 10 SUs

In Figure 7.42, it is also worth noting that with the increased number of SUs, the enhanced performance of the RECR-MAC protocol is better demonstrated, even though the PUs return over DCHs 2, 5, 8 and 10 during the multiple runs in this experiment. Considering 10 SUs, the RECR-MAC protocol saves approximately 33% to 40% communication time as compared to the other CR-MAC protocols. The abrupt curves show the PUs return during the communication. However, the BDC provides the opportunity to the SUs to continue the communication. The x-axis shows the number of SUs increases from 2 to 10, and the y-axis shows the communication time consumed by each pair of SU.

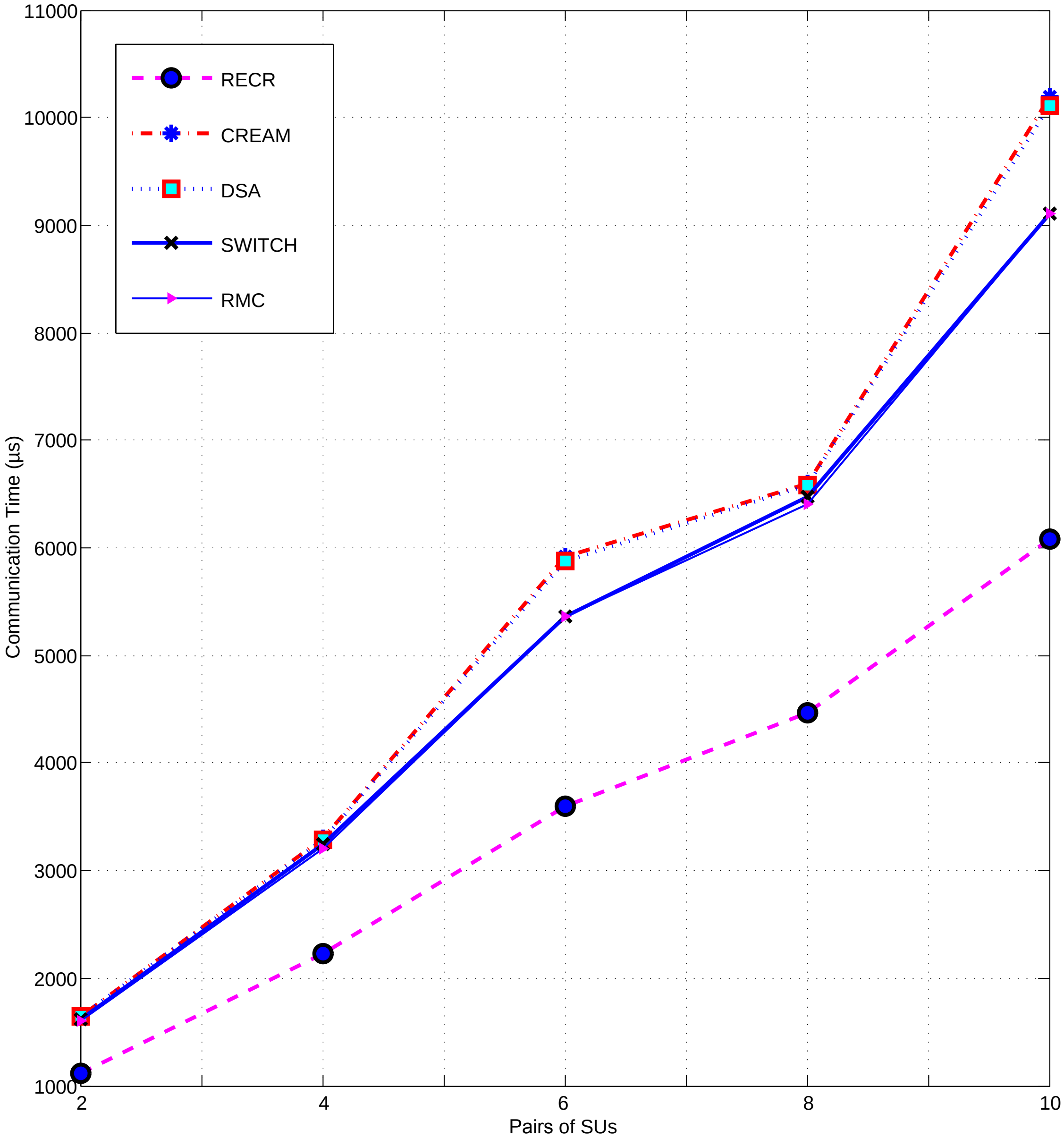

FIGURE 7.42: Communication time vs pairs of SUs of CR-MAC protocols

As mentioned above, the reduced communication time needs less transmitting energy to exchange data among SUs. Figure 7.43 shows that the RECR-MAC protocol requires less transmitting energy to successfully transmit their control and data information as compared to other CR-MAC protocols. The RECR-MAC protocol saves 33% to 40% transmitting energy as compared to the other benchmark CR-MAC protocols. The y-axis represents the energy transmitting by each protocol in this experiment. Saving energy is one of the major contributions to the design of the RECR-MAC protocol with and without PU returns. According to Figure 7.43, the RECR-MAC protocol is capable to save a lot of energy as compared to the other benchmark CR-MAC protocols.

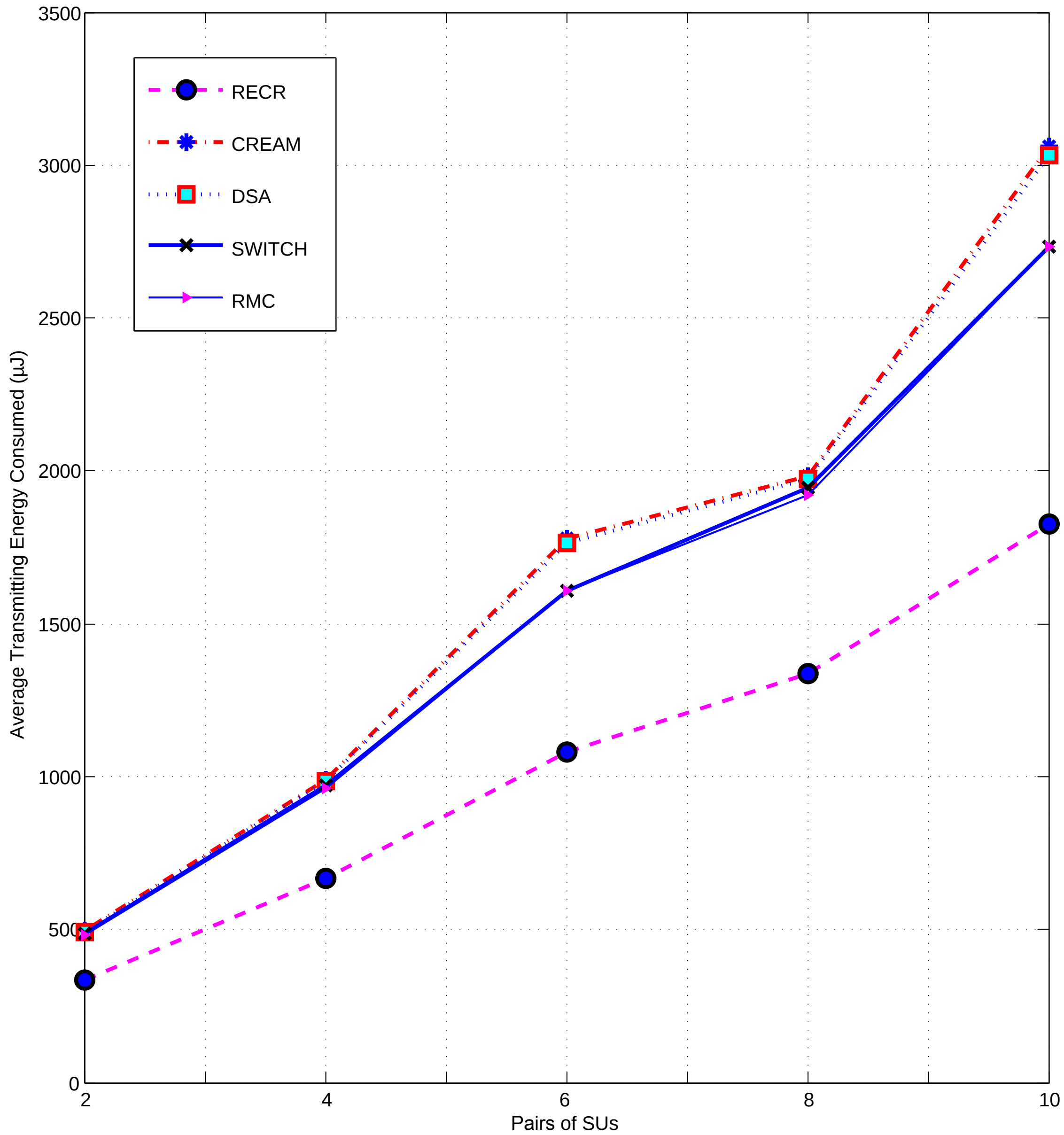

Figure 7.43: Transmitting energy consumed vs pairs of SUs of CR-MAC protocols

As discussed in the experiments 7.2.1 and 7.2.2, all CR-MAC protocols have utilised two DCHs for exchanging data frames among SUs. In experiments 7.2.3 and 7.2.4, all CR-MAC protocols have been exchanged their control and data frames according to their design as discussed in [20]

[58] [57] [23]. However, in this experiment, the throughput is investigated for a different number of SUs 2, 4, 6, 8 and 10 to make the model more robust. To conclude, Figure 7.44 illustrates that the RECR-MAC protocol achieves higher throughput as compared to other CR-MAC protocols with PU returns. The RECR-MAC protocol achieves more than three times higher throughput as compared to the benchmark CR-MAC protocols with PU returns shows the enhanced capacity and another achievement of the proposed RECR-MAC protocol.

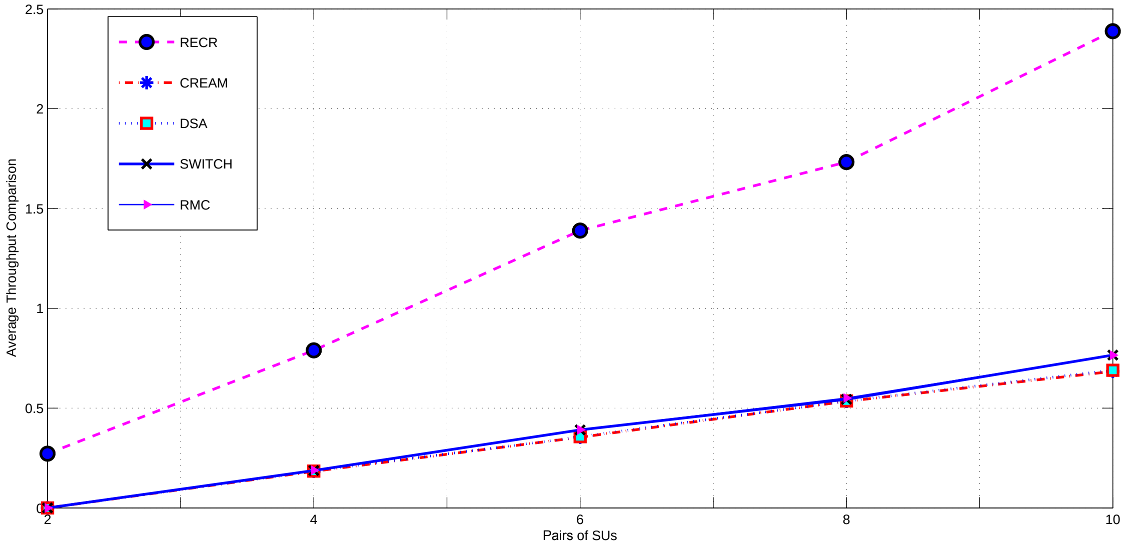

FIGURE 7.44: Average throughput comparison vs pairs of SUs of CR-MAC protocols

7.3 Summary and Contributions

This Chapter presented the performance analysis of the RECR-MAC protocol, with and without a backup data channel. The validity of the RECR-MAC protocol has been verified by changing the number of SUs, data channels, available time for SU communication, and the ON/OFF activity of the PUs during communication, with and without a BDC. It also has provided an extensive comparison of the RECR-MAC protocol with its benchmark CR-MAC protocols by using Matlab simulator. Furthermore, multiple experiments have been conducted to validate the ability of the proposed RECR-MAC protocol and its performance in terms of communication time and transmission energy consumption over the control and data channels, with and without PU returns. At the end, the throughput of the overall network has been analysed and the RECR-MAC and benchmark CR-MAC protocols compared. The conclusions including the summary of contributions and future work are presented in the next chapter.

Chapter 8

Conclusions and Future Work

This chapter presents the conclusions of the achieved research goals and discusses the enhanced design of reliable and efficient MAC protocols for CRAHNs. In addition, this chapter describes future research directions.

8.1 Summary of Contributions

In this thesis, numerous platforms and testbeds, classification model of the existing CR-MAC protocols, optimisation of the control frames, reducing the number of handshakes over the control and data channels, channel selection criteria and avoiding re-transmission have been proposed for reliable data communication in CRAHNs. In addition, the impact of PU activities on different channel selection strategies have been extensively studied and analysed. Moreover, a BDC has been introduced to continue the communication if a PU returns. It is also noted that the reliable channel selection strategy and BDC plays a vital role in reducing the communication time between SUs for task completion. The reduction in communication time between SUs over the control and data channels directly impacts the performance of CRAHNs in terms of energy consumption and throughput. Each chapter's contributions are summarised below.

In this thesis, numerous platforms and testbeds have been proposed to the existing researchers and potential cognitive technology users. The deployment of personal and commercial CR applications has been discussed in detail and the description of the proposed RECR-MAC protocol was briefly discussed. This thesis also discussed the CR-MAC protocol in depth and developed the classification model. This classification model covers multiple aspects of the technology such as network infrastructure, spectrum sensing and selection of control and data channels. Several DCH and BDC selection strategies for CRNs were suggested. The importance of PU activity and its impact on DCH and BDC selection criteria was noted during the investigation of the CR-MAC protocols in the literature.

The impact of channel selection criteria and BDC on the communication time, energy utilisation and throughput of CRAHNs is thoroughly discussed. The research shows that spectrum bands are not in scarcity, rather they are utilised inefficiently. Moreover, most of the CR-MAC protocols discussed randomly selected DCH for communication which might require additional time and energy to exchange control and data frames. Consequently, these factors reduce the network throughput. Thus, these existing challenges have been addressed in this research by designing a new CR-MAC protocol that overcomes the shortcomings highlighted in this thesis. The classification model of the CR-MAC protocols has been proposed according to an assessment of their nature, performance and communication based on the extensive literature evidence.

Many techniques have been proposed to reduce the communication time at the MAC layer, such as channel selection techniques, reducing collision, controlling overheads, optimising the control frames, reducing the number of handshakes over control and data channels, frame aggregation, reducing overheads and avoiding re-transmission. Based on this discussion, key characteristics that could increase the probability of successful message delivery between SUs in CRAHNs are as follows: **a)** A contention based IEEE 802.11 method where only the winner nodes start the communication whilst other participating SUs wait until the communicating SUs switch to the DCH, thus avoiding the hidden terminal problem. **b)** Optimised control frames and a reduced number of handshakes over the CCH to gain the extra transmission time for data communication. **c)** Selection of reliable channels based on least PU activity and other factors which ensures that transmission on the selected DCHs does not create interference with the PUs and reduces the number of re-transmissions. **d)** Channel selection criteria which ensure that the SU transmitters and receivers select channels with high ranking. **e)** Lastly, a novel BDC technique which re-establishes the link if a PU returns to its licensed channel. These adopted techniques are the main features of the RECR-MAC protocol which play a vital role in reducing the communication time between the SUs.

The model of the proposed protocol, RECR-MAC is developed and the aim and objectives of this research have been presented. The operational framework of the RECR-MAC protocol was divided into four phases based on its characteristics. The operation of this protocol has been thoroughly discussed in each phase of the flowchart. Each SU uses two transceivers and a sensor to avoid hidden terminal and multichannel hidden terminal problems. The CCH is assumed to be dedicated and always available for the SUs to exchange control frames. The functionality of the RECR-MAC protocol frame format is enhanced and the number of handshakes over the DCCH is reduced to enable more communication time for the SUs over the DCHs.

CR-MAC protocols have been classified into four groups to make it easily comprehensible. These groups allow researchers and commercial users to understand the properties and characteristics of the CR-MAC protocols. This thesis highlights on the basis of literature evidence that the CR-MAC protocols for Ad-Hoc networks mostly select random channels for data communication. The SUs may face high interference; PU returns over the selected random channel would require multiple re-connections and would decrease the probability of successful communication. Poor selection of DCHs may lead to high communication time, more usage of transmitting energy, and low network throughput. Some DCH selection strategies have been suggested for robust data communication. However, these strategies bring several challenges when more than one DCH is available in the cognitive network. Therefore, a channel selection strategy for data communication has been proposed to select reliable DCHs. The comparison of the random channel selection technique with the selection of the channel using criteria was classified into three phases, where the disadvantages of the random channel selection criteria and the importance of the reliable channel selection criteria are discussed in these phases. In addition, the BDC has been introduced to continue the communication if a PU returns. The impact of channel selection strategy and BDC over the proposed RECR-MAC protocol and its comparison with other benchmark CR-MAC protocols have been discussed in detail based on the proposed timing diagrams.

The performance analysis of the RECR-MAC protocol, in terms of communication time, energy usage and throughput and its comparison with other benchmark CR-MAC protocols with and without PU returns have also been discussed. Moreover, different payload sizes, for example 1000 bytes, 500 bytes and 50 bytes, have been exchanged over the control and data channels to validate the performance of the RECR-MAC and benchmark CR-MAC protocols. The analytical results have shown that the average transmitting energy consumed by the RECR-MAC protocol is lower than that of the other benchmark CR-MAC protocols, with and without PU interference. Furthermore, the RECR-MAC protocol has high throughput as compare to the benchmark CR-MAC protocols.

The impact of PU activity over the DCHs has been evaluated comprehensively and categorised into four patterns. In fact, it is a prerequisite of the SUs to first record PU activity before starting their communication. Regulatory bodies, such as the FCC and Ofcom do not allow SUs to interfere the licensed user traffic irrespective of the situation. Therefore, the impact of PU activities has been recorded by the SUs in order to utilise the channels effectively and efficiently during the time for which they are unoccupied. Furthermore, the RECR-MAC protocol and benchmark CR-MAC protocols have used the channel ranking strategy with and without a BDC; their communication time over the DCHs has been compared for multiple payload sizes. The obtained results show that the proposed protocol consumes the least amount of time over the DCCH. This allows SUs to transmit more data over the DCHs and leave more time for communication as compared to the benchmark CR-MAC protocols. Finally, the proposed RECR-MAC protocol consumes the least amount of communication time over the DCHs which may save more transmitting energy and provide higher throughput as compare to the other CR-MAC protocols.

Investigation revealed the performance analysis of the RECR-MAC protocol with and without a BDC. The validity of the RECR-MAC protocol has been verified by changing the number of SUs, DCHs, available time for SU communication, and the ON/OFF activity of the PUs during communication, with and without a BDC. This analysis has also provided an extensive comparison of the RECR-MAC protocol with its benchmark CR-MAC protocols under saturation conditions. Furthermore, multiple experiments have been conducted to validate the ability of the proposed RECR-MAC protocol and its performance in terms of communication time and transmitting energy consumption over the control and data channels, with and without PU returns. At the end, the throughput of the overall network has been analysed and the RECR-MAC and benchmark CR-MAC protocols are compared.

8.2 Limitations

The proposed RECR-MAC protocol has been designed to address the challenges and overcome the shortcomings of the existing CRAHNs protocols. The key aspect of the RECR-MAC protocol is the selection of primary and backup data channels, reducing the communication time and transmission energy between SUs and providing high throughput as compare to the benchmark CR-MAC protocols. However, it is important to discuss certain limitations of the RECR-MAC protocol. The control channel is assumed to be dedicated and always available to the SUs which may increase the cost to the network provider. Without assuming DCCH, it may introduce a large delay for the SUs to access and select the DCHs.

Another challenge is to avoid PU interference over the NDCCH and this may leave less time for SU communication over the DCHs. Furthermore, the RECR-MAC protocol must have at least two free DCHs to start the data communication, otherwise the SUs are unable to start operation which may reduce the opportunity for SUs to exchange their data if PU returns. It could be possible that the PU may return over both selected DCHs in RECR-MAC protocol. However, the channel selection strategy adopted in this thesis reduces the probability of PU returns during communication. According to the literature, more than 70% of the spectrums are available, indicating that the availability of free space is not an issue. It is possible that the performance of the RECR-MAC protocol could be improved by incorporating the features discussed above. However, the analytical and simulation results have indicated that the performance of the RECR-MAC protocol is better than that of the selected benchmark CR-MAC protocols.

8.3 Future Work

In this thesis, extensive research has been carried out to investigate the shortcomings of the existing CR technology for Ad-Hoc networks. The RECR-MAC protocol has been proposed to address such gaps discussed in Section 8.1. This work sets future directions for researchers and commercial users to integrate the proposed RECR-MAC protocol with different technologies and applications and develop the enhanced models in CRAHNs. The topics of interest that need to be investigated further in the future are described below.

8.3.1 Introduction of the NDCCH

To enhance the framework of the RECR-MAC protocol, the SUs may select their own CCH for each transaction instead of keeping the DCCH. Each pair of SUs needs to select a new CCH for the exchange of control information. As per the literature, a large part of the spectrum is unused in rural areas. Therefore, the introduction of the NDCCH to these areas would minimise the requirement of DCCH and reduce the cost to the network provider.

8.3.2 Security features of Cognitive Radio Networks

Security aspects are crucial in order to protect the network communication amongst authorised SUs within the networks. A compromise on security services reduces the reliability of the network and allows malicious users to access and control the network's resources. This would result in bringing the network performance down and all users could be affected by different types of attacks such as the man in the middle attack and denial of services. Moreover, the DCCH can be targeted by attackers, making it unavailable to legitimate SUs, which would stop the negotiation process over the CCH and prevent SUs from continuing their communication over the DCHs. Malicious users can make the available DCHs too busy for SUs and this affects the overall performance of the CRN.

8.3.3 Cross-layer Cognitive Radio Protocols

The integration of the cross-layers in CRN is not a new idea but it increases the overall network performance at a larger scale. The cross-layer based protocols integrate spectrum sensing at the PHY layer, the scheduling of packets at the MAC layer and select the most reliable and/or shortest path at the network layer. In particular, the cross-layer protocol allows the SUs to identify reliable channels and select the optimal path between sender and receiver. The proposed RECR-MAC protocol must consider the network and PHY layers along with MAC layer and use co-operation amongst multiple SUs to optimise the performance of the CRAHNs.

8.3.4 Integration of RECR-MAC with multiple applications and technologies

The integration of the proposed RECR-MAC protocol with multiple applications and technologies could provide direct benefits to a large number of wireless users, for example, social media applications such as Facebook and Twitter; chess and playing card gaming applications are not delay sensitive and their users could derive benefits from the proposed protocol.

Furthermore, mobile and Voice over Internet Protocol (VoIP) users could be able to make free calls by using the proposed RECR-MAC protocol. If cognitive features are enabled in any wireless device, this device is capable of detecting free space and utilising these applications and free calls. If a PU returns during the on-going process, then the users may switch back to their licensed channels and resume normal operation. However, if SUs take sensing time longer than the expected handshaking time over the CCH, then the transmitting time of the SUs could be reduced which adversely affect the QoS of mobile and VoIP traffic. In addition, the frequent PU returns during the communication for real time applications introduce the unnecessary mobility of the SUs among the spectrum bands which could decrease the network performance. Therefore, it is still challenging to effectively utilise CR technology for real time traffic.

8.3.5 Hardware Implementations

The hardware deployment of this technology is another important aspect that could be dealt with in the future. The operational framework of the RECR-MAC protocol provides connectivity to affected users during disaster conditions until the infrastructure is repaired. The integration of this protocol with existing testbeds, discussed in Chapter 1, could provide new and effective hardware in the field of wireless technology.

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Appendix

The summary of the thesis contributions is illustrated in the following figure:

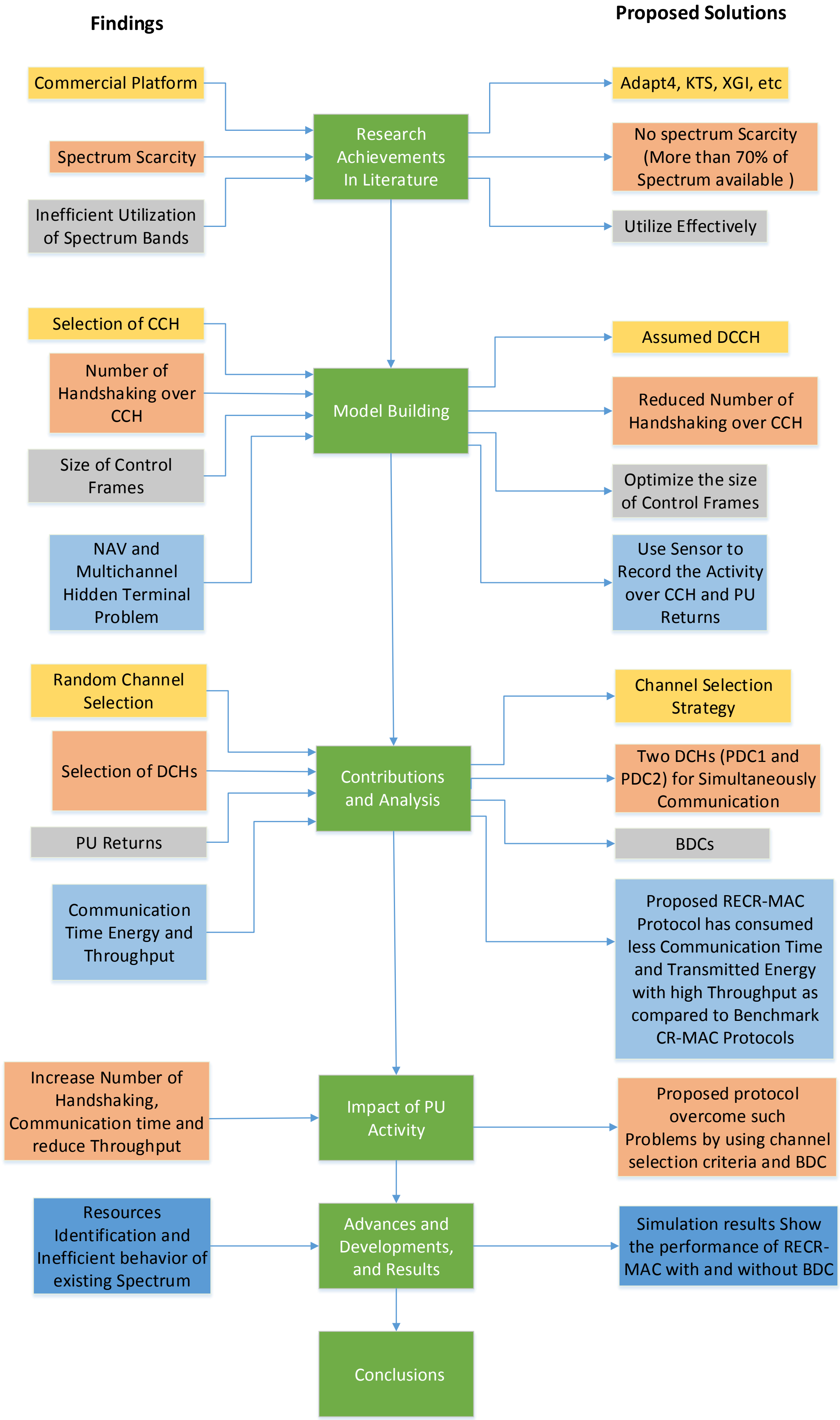

FIGURE 8.1: Summary of thesis contributions